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INTERNATIONAL
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STUDIES

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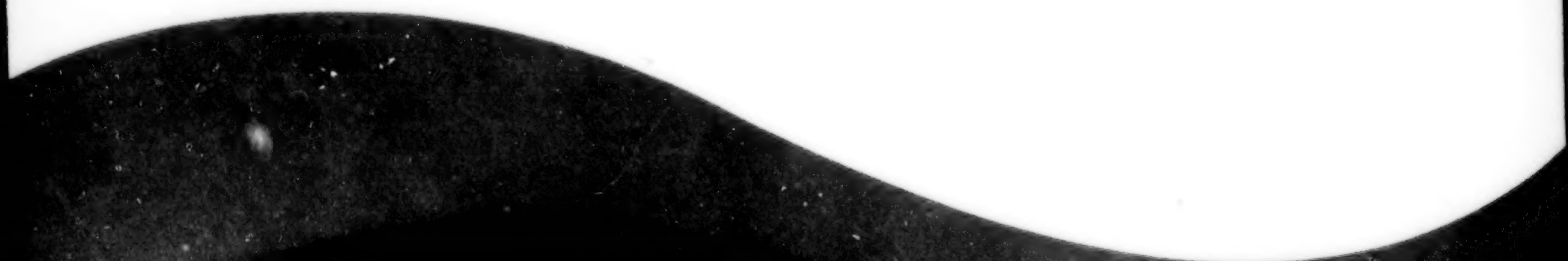
Program Summary



Setting Current Meter Moorings in Drake Passage from *R/V Thompson* in 1976

Program Summary
# of the
International Southern Ocean Studies

The U.S. Component of ISOS
is supported by the Office
for the International Decade
of Ocean Exploration of the
National Science Foundation

National Science Foundation

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Overview

The Southern Ocean is the center of the ocean's circulation system. It connects the waters in all three ocean basins. Because of this linkage, events in the Southern Ocean can have pronounced effects on North American climate even though the Southern Ocean is far from our shores. For these reasons it is important that ocean scientists understand the circulation of the Southern Ocean.

With the *Eltanin* circumpolar survey nearly completed, the International Southern Ocean Studies was initiated by the Foundation in 1974 as part of the International Decade of Ocean Exploration with the goal of furthering our understanding of the circulation of the Southern Ocean. Field experiments are now scheduled to be completed in September 1980. This project summary contains a complete description of the project activities.

Our understanding of Southern Ocean circulation has been advanced because of results from the International Southern Ocean Studies. Modern instrumentation and experimental methods used during the program have improved data quality and instrumentation recovery rate and a new generation of oceanographers are now involved in Southern Ocean problems. Initial scientific reports (which are also summarized in this document) indicate several important results: resolution of the volume transport through Drake Passage, identification of the banded structure of flow in Drake Passage, identification of eddies and intrusions as important mixing mechanisms in near-surface waters, and the importance of lateral mixing in the formation of waters at intermediate depths. Additional results will appear in scientific journals during the next few years.

These studies have made another step in understanding the role of the ocean in our life. They form a solid foundation on which to base future scientific studies.

M. Grant Gross
International Decade of
Ocean Exploration

Edward P. Todd
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Preface

This document is meant to summarize the scientific problems, progress to date and proposed direction for the program entitled "International Southern Ocean Studies (ISOS)". In preparing the present document, information was taken from various documents, publications and proposals prepared by ISOS principal investigators, and the assistance of these investigators is gratefully acknowledged. This document is by no means meant to give all of the scientific results that have been a result of ISOS experiments, but instead gives a brief description of the work encompassed by the ISOS program. Additional information concerning specific topics may be obtained from the various principal investigators or through the ISOS Administrative Office, Department of Oceanography, Texas A&M University, College Station, Texas 77843, U.S.A.

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1. Introduction

This report is dedicated to the scientists who have an interest in the physical oceanography of the Southern Ocean. It summarizes the results of the long-term physical oceanographic program in this region, named ISOS (International Southern Ocean Studies). Included are brief descriptions of the various ISOS field experiments, summaries of the work being done in the areas of theoretical modeling and historical data review and a list of all the pertinent scientific publications that have thus far resulted from ISOS.

Interest in the Southern Ocean has increased in the United States since the multi-disciplinary circumpolar survey on board the *USNS Eltanin* began in 1962. This survey was set up to provide the baseline physics, biology, chemistry, geology and geophysics of the Southern Ocean upon which all future work would be built. The Southern Ocean has unique features that make it of particular interest to the scientific community and of importance to mankind. For example, the divergent wind drift and intense temperature and salinity attenuations of the surface waters around Antarctica, caused by large-scale air-sea interaction, set up a meridional circulation pattern that carries great quantities of heat, salt and water from the northern abyssal waters into the Southern Ocean. This water upwells and is altered to cold antarctic water masses, which subsequently spread northward. The sea-air exchanges of heat, salt and momentum and the exchange of properties between water masses in this region are as vigorous as they are poorly understood. Of special global interest is the exchange of material across the sea-air interface, which couples the ocean with the atmosphere. The Antarctic is of particular significance because, through these waters, the abyssal waters of the world can interact directly with the atmosphere.

Areas of interaction between definable bodies of water whose boundaries are marked by relatively large gradients of temperature and/or salinity are fundamental; primary among these are frontal zones, continental margins and the main pycnocline. Of particular interest to the ISOS program have been studies of the formation of Antarctic Bottom Water and Antarctic Intermediate Water. Antarctic Bottom Water is the cold, dense water found deep within the Southern Ocean. It is thought to form in the near-surface waters along the continental margins of Antarctica. Since it is denser than the surface and intermediate waters, it sinks and spreads as a layer along the bottom of the Antarctic basins and northward into the major ocean basins. Antarctic Intermediate Water is formed within the Polar Frontal Zone between 45° and 55°S. (This will be discussed in detail later in this report.) Its characteristic indicators are a salinity minimum (relative to waters above and below it) and a relative oxygen maximum. From its place of origin, it sinks and spreads northward to approximately 900 m depth into the major ocean basins. It exists as an identifiable water type as far north as 25°N in the North Atlantic.

In 1972, the Office of Polar Programs of the U.S. National Science Foundation requested the committee on Polar Research of the National Academy of Science to prepare a ten-year plan for future work in physical oceanography in the Antarctic. An *ad hoc* group produced the report "Southern Ocean Dynamics: A Strategy for Scientific Exploration, 1973–1983". (This report is available from the Polar Research Board, 2101 Constitution Avenue, Washington, D.C. 20418, U.S.A.).

In 1973, a group of physical oceanographers, using this report as a base, prepared a proposal for a long-term research program in physical oceanography of the Southern Ocean. This program, International Southern Ocean Studies (ISOS), was officially approved in 1974 and has received its U.S. support from the Office for the International Decade of Ocean Exploration of the National Science Foundation. The U.S. contingent of ISOS investigators have come from the Lamont-Doherty Geological Observatory of Columbia University, Nova University, Oregon State University, Pacific Marine Environmental Laboratories of the National Oceanic and Atmospheric Administration, Texas A&M University, the University of Southern California, the University of Washington and the Woods Hole Oceanographic Institution. Since its conception, the program has expanded into a truly international one with cooperation between scientists from Argentina, Australia, Canada, Chile, Denmark, England, France, Japan, Norway, South Africa, USSR and West Germany. Financial support, including ship time, has been derived from a number of these countries.

The program of International Southern Ocean Studies (ISOS) is an attempt to improve our understanding of the circulation in this region. It has been designed to draw on current technology and to be carried out in the time frame of the Global Atmospheric Research Program (GARP) and the First GARP Global Experiment (FGGE). The ISOS is recognized as a component of the International Decade of Ocean Exploration (IDOE) by the Intergovernmental Oceanographic Commission of UNESCO. In the context of the IDOE, ISOS is a regional and process-oriented study whose design draws on the results of other such studies in other regions without attempting to repeat them.

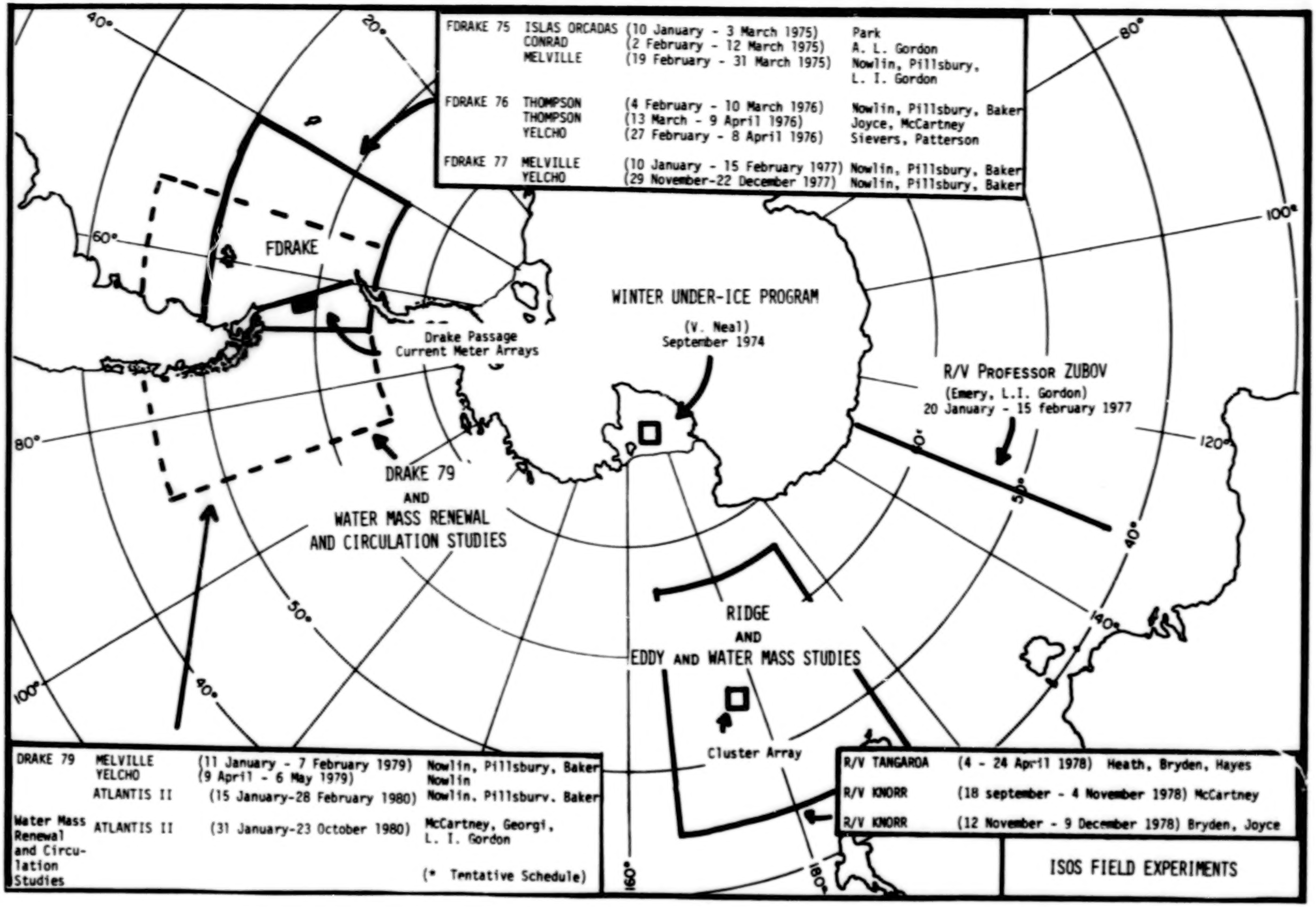
The objectives of ISOS are:

1. To identify the statistical properties and space-time scales of variability in selected regions of the Antarctic Circumpolar Current system;
2. To develop and subject to critical test theories of dynamical balance, mixing, and exchange with other oceans; and
3. To develop a basis for understanding the role of the large-scale circulation and air-sea interaction in the Southern Ocean in global climate dynamics.

The objectives are being met through a sequence of monitoring and dynamics experiments in the Drake Passage and New Zealand sectors of the Antarctic Circumpolar Current system, long-term monitoring of certain large-scale properties, analysis of existing data sets, and numerical, analytical, and laboratory modeling.

The scientific direction of ISOS is determined by a Scientific Council consisting of the principal investigators of the ISOS projects within the U.S., representatives of the various foreign institutions involved in ISOS and other scientists interested in the program. This Scientific Council meets annually within the U.S. for a period of about one week. During that meeting, results of the previous year's activities are presented and discussed, long-range plans are formulated and specific field activities for the coming year are coordinated. The ongoing direction of ISOS has been vested in a smaller Executive Committee consisting of D. J. Baker, Jr. of the University of Washington, A. L. Gordon of Lamont-Doherty Geological Observatory, M. S. McCartney of the Woods Hole Oceanographic Institution, W. D. Nowlin, Jr. of Texas A&M University, R. D. Pillsbury of Oregon State University and B. A. Warren of the Woods Hole Oceanographic Institution. In practice, the day-to-day coordination and administrative activities are carried out by the ISOS Scientific Officer, J. M. Morrison, at Texas A&M University under the direction of the co-chairmen of the Executive Committee, Baker and Nowlin. The international coordination and liaison was spearheaded by the ISOS International Coordinator, V. T. Neal, of Oregon State University until the spring of 1979. This function is now being carried out by the ISOS administrative office at Texas A&M University.

The past, ongoing and planned activities which comprise the ISOS program are summarized in this document. Included are brief descriptions of the ISOS field experiments and theoretical activities. Following ISOS objective (1), the ISOS field work has been essentially limited to the Drake Passage region and the region south of New Zealand. Figure 1 is a chart summarizing the geographical and time distribution of the ISOS field experiments. To date, the ISOS theoretical activities have been quite moderate. It is hoped that with the end of the field activities, more interest will be generated in the interpretation of the data collected and application of the various ideas generated to models of the Southern Ocean. Present plans call for the termination of the ISOS field experiments during 1980 and to devote one or two years to the analysis, interpretation and publication of results. During 1980 or 1981, there are tentative plans to hold a special Chapman Conference of the American Geophysical Union on Southern Ocean Dynamics. It is hoped that this meeting will stimulate the interest of both experimentalists and theoreticians in working with the data and ideas generated by the ISOS field work. It seems likely that the results of this conference will form the scientific basis for the planning of a subsequent program to continue the study of physical oceanography of the Southern Oceans during the 1980's.



FDRAKE 75	ISLAS ORCADAS	(10 January - 3 March 1975)	Park
	CONRAD	(2 February - 12 March 1975)	A. L. Gordon
	MELVILLE	(19 February - 31 March 1975)	Nowlin, Pillsbury, L. I. Gordon
FDRAKE 76	THOMPSON	(4 February - 10 March 1976)	Nowlin, Pillsbury, Baker
	THOMPSON	(13 March - 9 April 1976)	Joyce, McCartney
	YELCHO	(27 February - 8 April 1976)	Sievers, Patterson
FDRAKE 77	MELVILLE	(10 January - 15 February 1977)	Nowlin, Pillsbury, Baker
	YELCHO	(29 November-22 December 1977)	Nowlin, Pillsbury, Baker

DRAKE 79	MELVILLE	(11 January - 7 February 1979)	Nowlin, Pillsbury, Baker
	YELCHO	(9 April - 6 May 1979)	Nowlin
	ATLANTIS II	(15 January-28 February 1980)	Nowlin, Pillsburv, Baker
Water Mass Renewal and Circulation Studies	ATLANTIS II	(31 January-23 October 1980)	McCartney, Georgi, L. I. Gordon
			(* Tentative Schedule)

R/V TANGAROA	(4 - 24 April 1978)	Heath, Bryden, Hayes
R/V KNORR	(18 september - 4 November 1978)	McCartney
R/V KNORR	(12 November - 9 December 1978)	Bryden, Joyce

Figure 1. ISOS Field Experiments

2. Field Experiments

The purpose of the ISOS program has been to improve our understanding of the Antarctic Circumpolar Current (ACC) by: 1) identifying the space and time scales of variability of the ACC and its statistical properties in selected regions; 2) developing and testing theories of dynamical balance; 3) developing a basis for understanding the role of the large-scale circulation and air-sea interaction in the Southern Ocean in global climate dynamics; 4) developing an understanding of Polar Frontal Zone dynamics and their relationship to the ACC; and 5) improving our understanding of the methods of water mass formation, mixing and exchanges with other oceans.

In order to achieve these goals a sequence of kinematical and dynamical field experiments were initiated. These include a program of long-term monitoring of the ACC in the Drake Passage region, field studies of the Polar Frontal Zone, studies of the water mass renewal and circulation of the Subantarctic Zone and measurements of winter oceanographic conditions beneath sea ice. In addition, analyses of the historical data sets and laboratory and numerical modeling studies have been made.

2.a. Long-term Studies of the ACC at Drake Passage

FDRAKE. Because of the limited amount of personnel and equipment available to the ISOS program, it was decided to limit our initial studies of the Antarctic Circumpolar Current (ACC) to the Drake Passage region. The first experiment, entitled FDRAKE (First Dynamic Response and Kinematic Experiment), began during the austral summer of 1974–75 and continued through the austral summer of 1977–78. FDRAKE was designed to begin a description of the energy-containing space and time scales of the ACC and its spatial relation to the Polar Frontal Zone in the Drake Passage and western Scotia Sea. Specific studies were aimed at the following aspects of the ACC system: (1) to describe the energy-containing space and time scales in the Drake Passage in order to design a major kinematic and dynamic experiment for the ACC to be carried out during FGGE, and (2) to describe selected property distributions within the Drake Passage and western Scotia Sea for the continuing study of mixing processes, particularly in the Polar Frontal Zone (PFZ), which may be involved in the formation of Antarctic Intermediate Water. Brief descriptions of the field work carried out in Drake Passage from 1974 to 1978, as well as a summary of the significant results of FDRAKE follows.

FDRAKE 75. The first major ISOS field program was initiated during January-March 1975 in the Drake Passage and western Scotia Sea (Neal, 1974). Three ships were involved in the program: *R/V Conrad* and *R/V Melville* of the U.S.A. and *ARA Islas Orcadas* of Argentina (locations of stations occupied by each vessel are shown in Figure 2)

Chief scientist Dr. Kilho Park and other scientists from the University of Washington, Texas A&M University, Instituto Antartico Argentino, Oregon State University and Universidad Catolica de Valparaiso (Chile) were at sea from 10 January to 3 March on board *ARA Islas Orcadas* studying the physical and chemical properties of the region (Wearn and Park, 1975). Measurements were made of the thermohaline and nutrient distributions across Drake Passage and in the western Scotia Sea. A total of 85 STD (salinity/temperature/depth) profiles and 34 hydrographic stations were completed. Water samples were processed aboard ship to obtain salinity, oxygen, phosphate, silicate and nitrate concentrations. About one-half of the profiles were made to within a few meters of the bottom; the rest extended to approximately 1200 meters. Temperature profiles were made between stations using expendable bathythermographs (XBTs).

Chief scientist Dr. A. L. Gordon (Lamont-Doherty Geological Observatory, Columbia University) and other scientists from Lamont-Doherty Geological Observatory and the Instituto Antartico Argentino worked on board *R/V Conrad* from 2 February to 12 March (A. Gordon, 1975). A total of 59 STD stations were occupied. Water sampling bottles were used to obtain data on the distribution of oxygen, silicate, phosphate, carbon dioxide, tritium, copper and iron. XBTs were used to obtain temperature profiles between stations. The sampling was planned to delineate the thermohaline structure of the Polar Frontal Zone and the Antarctic Circumpolar Current. *Conrad* and *Islas Orcadas* rendezvoused near 57°S, 55°W (see Fig. 2), where STD and XBT profiles were made every 16 km along north-south sections in order to study the three dimensional thermal structure of the Polar Front. *Conrad* also made stations in the eastern Bransfield Strait and within the Weddell-Scotia Confluence between the waters of the Weddell Sea and Scotia Sea.

Work aboard *R/V Melville* was under the direction of Dr. W. D. Nowlin, Jr. (Texas A&M University) with participating scientists from Oregon State University,

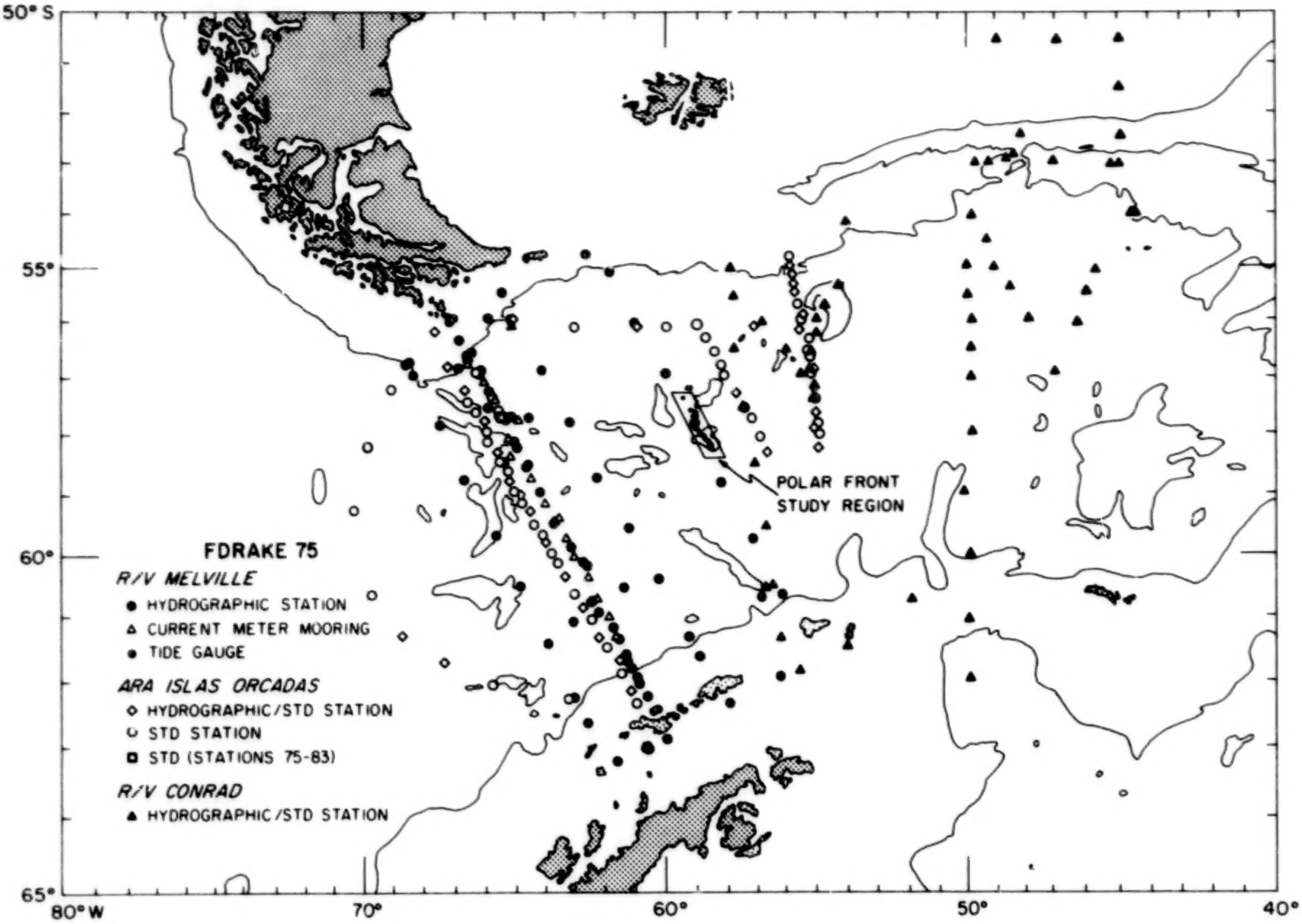


Figure 2. Location of FDRAKE 75 stations and moorings. These stations were occupied during January-March 1975 using *R/V Melville*, *ARA Islas Orcadas* and *R/V Conrad*.

Texas A&M University, Scripps Institution of Oceanography, Instituto Hidrografico de la Armada de Chile, and Servicio de Hidrografico Naval de Argentina (Nowlin *et al.*, 1975). *Melville* worked in the Drake Passage and western Scotia Sea region from 19 February to 31 March. Five hydrographic sections were made across Drake Passage; one section was made through Bransfield Strait and one across the western Scotia Sea to the east of Drake Passage.

During the *Melville* cruise, long-term monitoring of the temperature, pressure and velocity fields of the ACC in Drake Passage was begun. Forty-three current meters on 15 moorings and four internally-recording tide gauges were deployed in the passage (see Figure 1 for locations and Figure 3 for configurations relative to the observed thermal structure). Twenty-seven of the current meters contained temperature as well as current sensors. Seven of the current meter moorings and two tide gauges were retrieved approximately three weeks after deployment. The remaining eight current meter moorings and two tide gauges were left in place to obtain year-long records. All of the 24 short-term current meters were recovered: 21 gave good records for the full time, 1 yielded a 6-day record, 1 yielded a 70-hour record and 1 failed completely. Of the 16 short-term temperature records, 14 produced good records, but only the tide gauge near Cape Horn returned a complete record (Pillsbury *et al.*, 1976, 1977).

The hydrographic work done on *Melville* in Drake Passage was designed to determine the density structure and distribution of chemical properties in the vicinity of the current meter array. Ninety hydrographic stations were occupied, 63 of which combined both STD and standard sampling bottle casts. In addition to temperature and salinity data, samples for oxygen, silicate, phosphate, nitrite and nitrate analysis were taken at discrete depths to near the bottom.

FDRAKE 76. In 1976 two ships operated out of Punta Arenas, Chile as part of FDRAKE 76: *AGS Yelcho* of the Chilean Navy and *R/V Thomas G. Thompson* from the University of Washington. The first two legs of the *Thompson* cruise were planned to obtain spatial and temporal data on the meso- and large-scale variability of the ACC in Drake Passage (Nowlin *et al.*, 1976). Station and mooring locations are shown in Figure 4. Leg III of *Thompson* was devoted to a study of the PFZ in conjunction with *Yelcho*. This study will be discussed in Section 2.d.

Leg I was devoted primarily to the recovery of shallow pressure gauges and current/temperature recorders placed in Drake Passage during FDRAKE 75

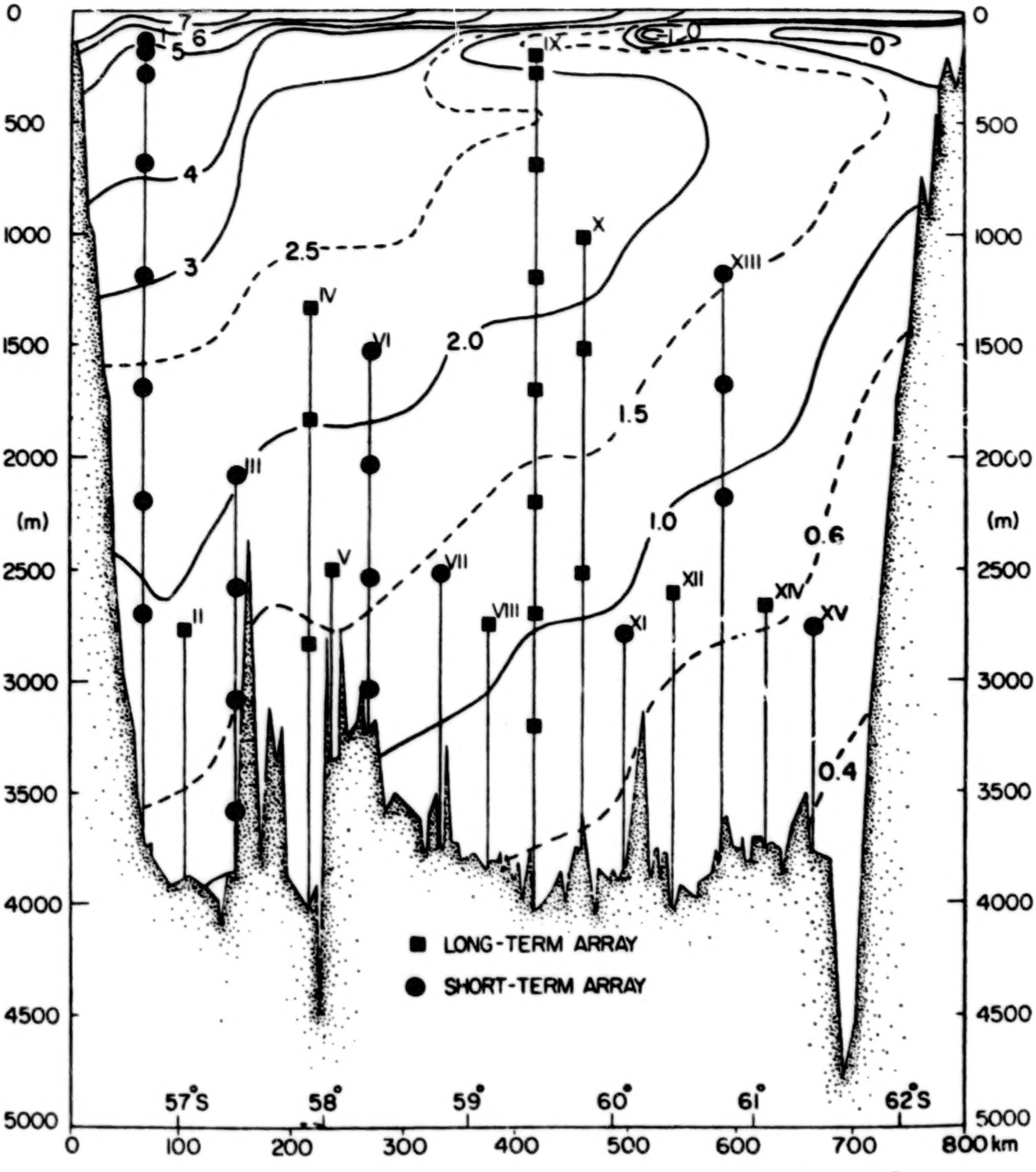


Figure 3. FDRAKE 75 current meter moorings in relation to observed temperature structure (°C).

and to the installation of another long-term array of recording instruments. Of the 21 instruments, 19 were recovered. One tide gauge off Cape Horn and one current/temperature/pressure recorder were lost (Pillsbury *et al.*, 1977). A new array of 11 current/temperature/pressure recorders on 7 moorings was deployed. Five deep pressure sensors on three recorders were also moored at the northern and southern ends of the passage to provide information on the long-term variation of flow through the region. Shallow pressure recorders were again moored on the shelves near Cape Horn and Livingston Island. The configuration of the 1976 array is displayed in Figure 5.

During Legs I and II, hydrographic and STD stations were taken in the passage and along the east-west trench at the southern end of the passage. Studies of the water mass distributions and chemical balances in the area were enhanced by the collection of high quality chemical data. A computer-compatible Auto-Analyzer II was used on board to determine concentrations of phosphate, nitrate, silicate and nitrite.

Four experimental NDBO (National Data Buoy Office) satellite-tracked surface drifters were launched from *Thompson*. Although they were transmitting and being received by satellite prior to launching, all failed within 11 days of being launched.

Near Livingston Island, *R/V Thompson* rendezvoused with the Soviet research vessel *Professor Viese*, which had been making current measurements and

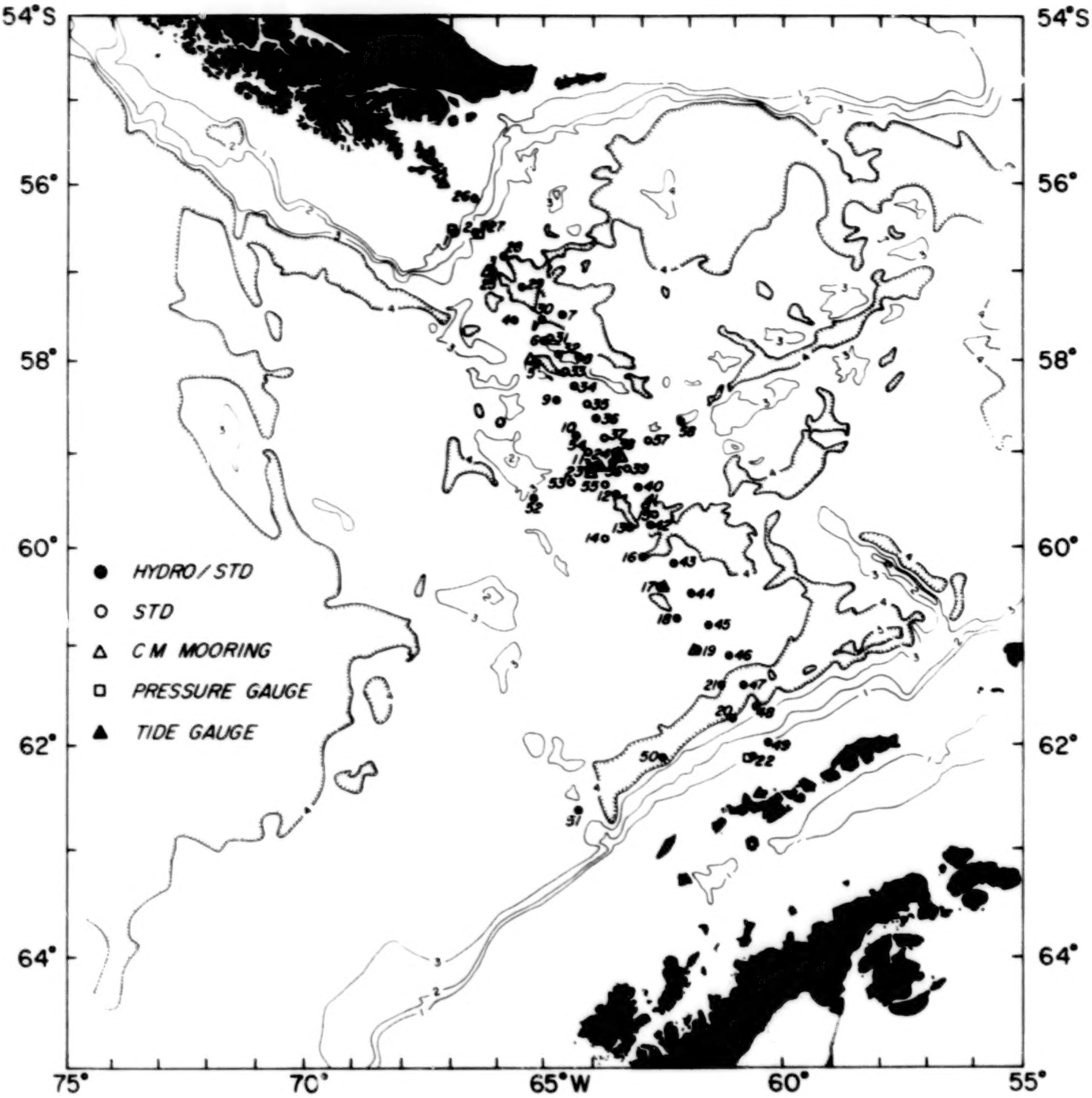


Figure 4. Positions of stations occupied and moorings deployed during Legs I and II aboard *R/V Thompson* during FDRAKE 76.

hydrographic/STD observations to the west of *Thompson* activities. At rendezvous salinity, oxygen and nutrient standards were exchanged and simultaneous hydrographic and STD measurements were made for intercalibration (L. Gordon *et al.*, 1977).

FDRAKE 77. During January and February 1977, the third phase of the field work in the FDRAKE was carried out in the Drake Passage on board the *R/V Melville*. A U.S. scientific team was led by Drs. Worth D. Nowlin, Jr. of Texas A&M University and R. Dale Pillsbury of Oregon State University and included scientists from the Instituto Hidrografico de la Armada de Chile and the Instituto Antartico Argentino (Whitworth, 1977). *Melville* sailed from Valparaiso, Chile on 10 January.

Six of the seven moorings deployed during FDRAKE 76 were recovered, but attempts to recover the mooring near 58°S, 65°W were unsuccessful. The tide gauges at each side of the passage, as well as deep pressure gauges which were deployed the previous year, were also recovered. Of the nine current meters recovered, seven provided more than 10 months of data. Two of the three pressure gauges produced records of one-year duration; one produced only a 5½-month record.

Most of the current meters recovered were refurbished in the field for redeployment. Data tapes were translated and analyzed on board to check the performance of the meters and the thermistors, and compasses were recalibrated. Twenty-one current meters were deployed on five moorings in a "cluster" array (Figure 6) in the central part of the passage. This array was designed to measure the variability of currents and temperature on space scales of 10 to 60 km during a period of approximately one year. Pressure gauges were also installed on each side of the passage. In addition to launching a total of 109 XBTs during the

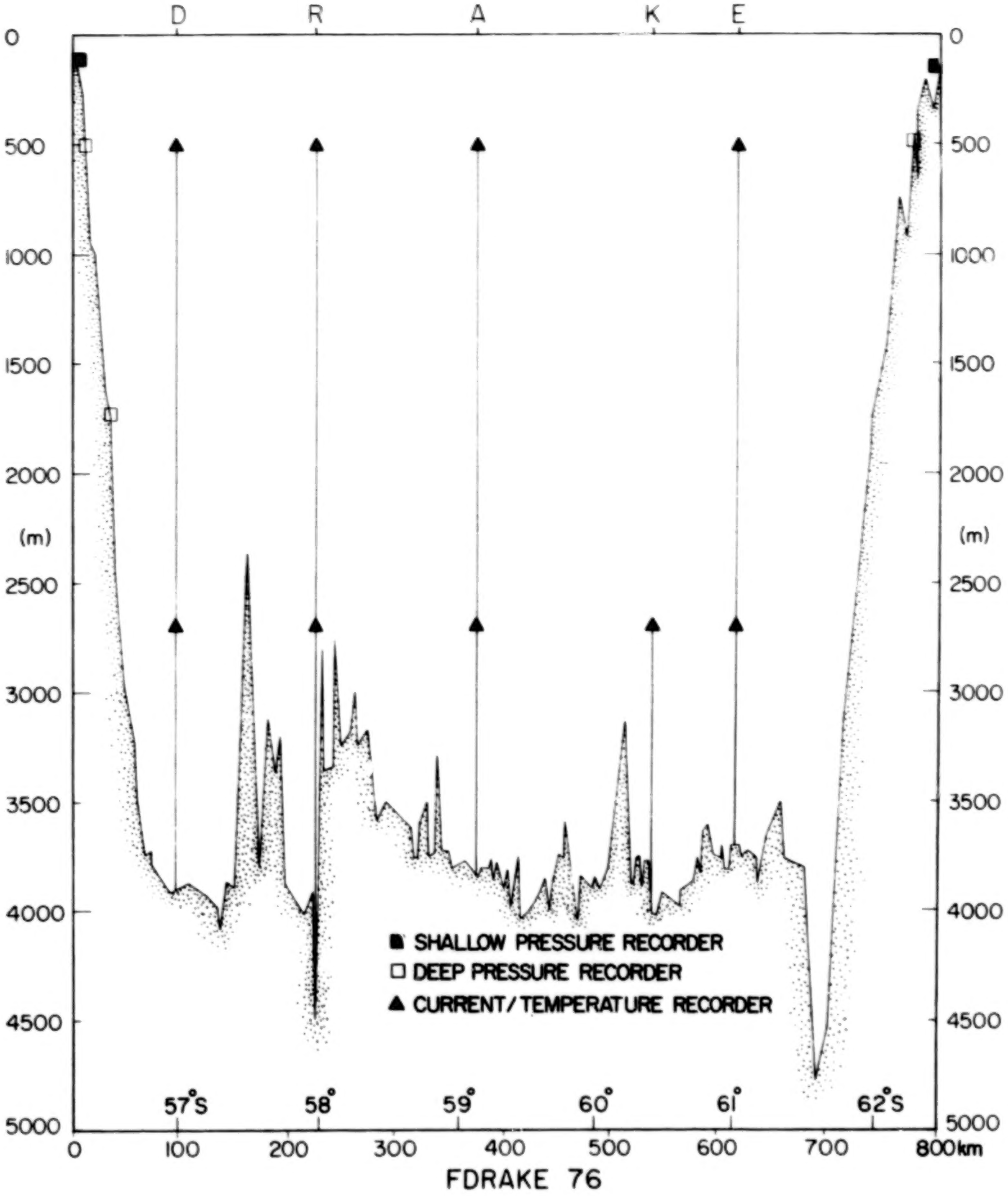


Figure 5. The FDRAKE 76 current meter array. Current meters were also moored at 2700 m at a distance of 25 km up- and downstream from mooring "A".

cruise, hydrographic/STD stations were occupied before and after deployment of the new array (Figure 7). The density field determined from the data provides a base to be used in interpreting the temperature and velocity data obtained from the moorings.

In December of 1977 a team of Chilean and U.S. scientists from the Instituto Hidrografico de la Armada de Chile, University of Washington, Texas A&M University and Oregon State University concluded the FDRAKE using the Chilean naval vessel *AGS Yelcho*. All 21 of the current/temperature recorders were recovered and another year-long current meter mooring was set in the center of the passage. The deep sea pressure recorders from either side of the passage were recovered; they each produced a good year-long record. On each side of the passage, two deep-sea pressure recorders were deployed on the bottom at 500 m.

Argentine Winter Cruise. During the 1976 austral winter, scientists from the Instituto Antartico Argentino directed a physical oceanography cruise aboard the *ARA Islas Orcadas* in the Drake Passage. Ice cover extending northward to approximately 60°S precluded a full hydrographic section across the passage.

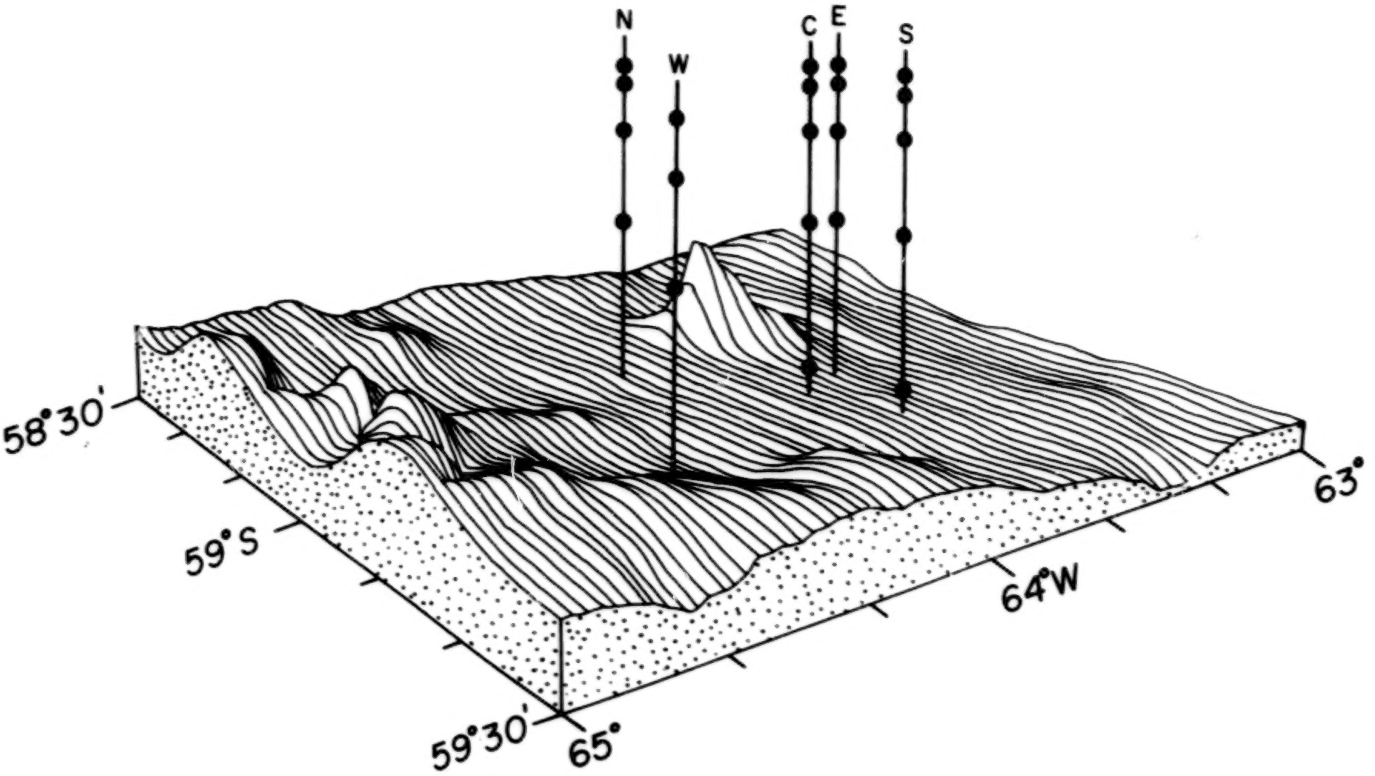


Figure 6. The FDRAKE 77 cluster of current meter moorings in the relatively flat region of central Drake Passage. Vertical extent of moorings is approximately 3800 m.

North-south sections of deep hydrographic/STD observations were made across the ice-free zone. In addition, 1500-m stations were made in a zig-zag pattern to determine the transition between the Polar Frontal Zone and the Antarctic Surface Waters. At one station within the Polar Frontal Zone, STD's were taken hourly for 24 hours. Surface and meteorological observations were taken at each station. Data from this cruise have been reduced by scientists from the Instituto Antartico Argentino and Texas A&M University.

Significant Results of FDRAKE. Analysis of data collected during FDRAKE field operations yielded several significant results which were used in the design of DRAKE 79. The major findings are described in Baker, *et al.* (1977) and below.

In the Drake Passage three bands of relatively high speed flow separate regions of distinct water masses (Nowlin *et al.*, 1977). The high speed bands of flow exist between: 1) Subantarctic Surface Water and the northern extent of the transition Polar Frontal Zone; 2) the southern boundary of the Polar Frontal Zone and the Antarctic Surface Water; and 3) the Antarctic Surface Water and the Continental Water. These streams change in spatial configuration; lateral movements of as much of 100 km in two to three weeks have been observed. The central core has shown the greatest meridional movement. The flows extend below the lower depths of the different water masses and are vertically coherent to the bottom except in regions where large topographic features exist. Such features disrupt the vertical coherence up to several hundred meters above the shallowest relief.

Hydrographic measurements in Bransfield Strait show different properties within the three basins in the Strait (Gordon and Nowlin, 1978). Apparently bottom water in these basins is renewed locally on time scales of 10 years or less. These basin waters do not significantly affect waters outside the Strait below sill depth (about 1100 m) of the basins.

Several different estimates of the transport through Drake Passage were made. FDRAKE and historical hydrographic data gave an average *geostrophic transport relative to 3000 m* of 101 ± 12 Sv. Concurrent hydrographic and current meter measurements were combined to give an estimate of *total transport.* Nowlin *et al.*, (1977) used the first three weeks of current meter data collected in 1975, when 12 deep (2700 m) current records were available, to estimate a total transport of 124 ± 15 Sv. (95 Sv. of which is the geostrophic transport relative to 2700 m). The total transport can be considered as the sum of the baroclinic geostrophic transport relative to 2700 m, plus the *barotropic transport,* which was estimated from the deep current meter records. Two such estimates were made from the period in 1975 when 12 deep current meter records were available (Fandry and Pillsbury, 1979). Using objective analysis techniques, weekly averaged through-passage speeds gave estimates of the barotropic transport of −9 ± 4.5 Sv. and 27 ± 4.5 Sv. From the six 1975 long-term (35 week) current records, weekly averaged data yielded 35 objectively calculated barotropic transports which ranged from −70 ± 14Sv. to 150 ± 14 Sv. The average of all 35 estimates was 27 ± 14 Sv. Pressure gauge data from 500 m depth showed that the average downstream velocity varies by 2.5 cm/sec during the year. Assuming that this

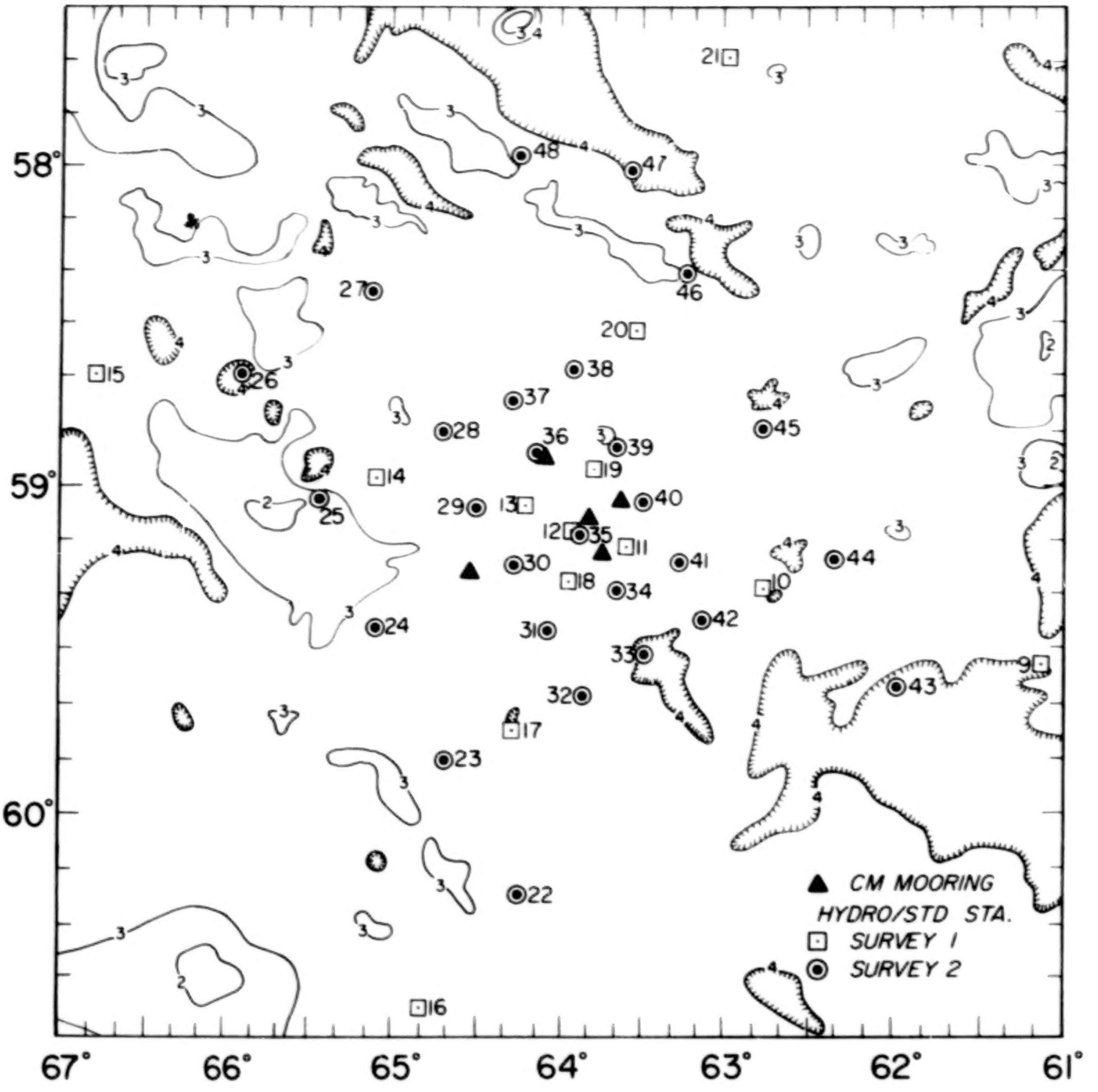


Fig. 7. Positions of the FDRAKE 77 current meter array and hydrographic/STD stations.

velocity fluctuation is barotropic and that geostrophic transport remains constant, the variability in total transport would be 65 Sv. (Wearn and Baker, 1980a).

Considerable meridional exchange of heat may take place across the Antarctic Circumpolar Current system and provide for the modification of the surface waters to form Antarctic Bottom Water or components of Antarctic Intermediate Water. ISOS observations have revealed that meanders in the current cores can develop in closed rings (A. Gordon *et al.*, 1977; Emery and Savchenko, 1977; Joyce and Patterson, 1977b). Ring formation, movement and decay represent a mechanism for the exchange of heat, salt and momentum across the cores within the ACC system.

Kinematic scale information has been obtained from repeated hydrographic sections and from three year-long current meter arrays. Fluctuations in temperature and velocity are very highly correlated vertically except near the bottom where topographic effects become important. Velocity fluctuations at deep meters precede slightly those at mid-depth.

In the Central Passage horizontal fluctuations in velocity from year-long records are significantly correlated at separations up to 40 or 50 km. Temperature fluctuations have larger scales and are correlated at 80 km. Coherence estimates confirm that high correlations are principally due to low frequency fluctuations with periods longer than 10 days.

Preliminary analyses suggest that sporadic lateral movements of fronts may result in reduced correlation lengths when calculated from year-long records due to changes in propagation direction. Correlations between Central Passage moorings over selected 30- to 90-day periods tend to be higher than those for year-long records.

The statistics from moorings across the Passage suggest that there are two or three distinct flow regimes within the ACC. The Northern Passage regime is characterized by highly fluctuating currents and relatively steady water mass properties. The current variations in the Central Passage are much smaller on a year-long basis but are pronounced during periods of large temperature change. It is thought that this may be due to lateral movements of water mass boundaries (fronts). The Southern Passage records are less variable in both temperature and velocity.

Spectra of fluctuation kinetic energy further emphasize the variability of the ACC in the Northern Passage; there is an order of magnitude more energy there than in the rest of the Passage. All spectra show a clear peak in the energy at 14 days—probably due to the lunar fortnightly tide.

At two locations, data from 1975 and 1976 moorings have been combined, and the resulting spectra show a six-month periodicity. This period is also apparent in the southern pressure gauge record and the southern hemisphere winds. A high coherence between surface winds and currents at 1000 to 2500 m at a period of 5.5 days has also been found (Baker, *et al.*, 1977).

The two-year data series from the pressure gauge program has yielded new and interesting results. The diurnal and semi-diurnal tides dominate the pressure record, as expected. A low-passed record shows high energy levels in the 14-day and semi-annual periods, particularly in the southern record. The northern record shows more of an annual cycle, but it is not well defined. The pressure difference shows energy in the 80–90 day period as well as annual, with fluctuations (at 500 m) of the order of 20–30% of the mean (Wearn and Baker, 1980a).

The bottom temperature records show an annual cycle with opposite behavior on either side of the passage: the southern record is cold in the winter, warm in the summer; the northern record is warm in the winter, cold in the summer. McCartney has suggested that the warm winter water at 500 m at the north is Subantarctic Mode Water (SAMW) advecting in from the west and has proposed study of the annual cycle for the SAMW for 1979.

DRAKE 79. On 20–22 March 1978 a meeting of interested scientists was held at Oregon State University to discuss the results of FDRAKE and develop a plan of activities for the Drake Passage region during the period of December 1978-March 1980. Using the knowledge gained during FDRAKE, the following goals which might be achieved during this experimental period, designated as DRAKE 79, were identified:

- Monitor transport through Drake Passage
- Relate variability of transport to wind forcing
- Calibrate $\frac{\partial}{\partial t}[\Delta p \mid 500\text{ m}]$ from pressure gauges using the cross-passage integral of through-passage measured speed at 500 m
- Investigate shelf-deep ocean interactions at north and south edges of the Passage
- Verification/determination of selected time and space scales:
  - for through passage separations >60 km
  - in Northern Passage where there is rough topography & convergence of the flow
  - in the Southern Passage
  - of vertical coherence over rough bottom
- Study winter convection/modification/advection of Subantarctic Water into/within Drake Passage
- Investigate vertical variation in horizontal velocity as a possible source of water mass modification (evidenced by T-S profiles)
- Obtain weather and tidal data from Isla Diego Ramirez
- Describe changes of temperature field and locations/characteristics of frontal zones in Drake Passage section
- Obtain and study longer current and temperature records from mid-passage
- Delineate phenomena and describe their propagation/modification within array area
- Comparison of data from moored array with drifter data
- Describe eddy-mean flow interaction using data from a fixed array
- Estimate geostrophic zonal heat flux

It was decided that the scientific objectives of DRAKE 79 should be limited to four general objectives: (1) to interrelate changes in thermal structure and currents within the Antarctic Circumpolar Current (ACC), its transport fluctuations, cross-stream pressure fluctuations and large-scale atmospheric forcing in the Southern Hemisphere; (2) to monitor the transport of the ACC through Drake Passage; (3) to better describe meso-scale features of the ACC; and (4) to refine estimates of turbulent fluxes of heat and salt across the ACC. Transport monitoring includes both measuring currents and estimating the density field to give both the baroclinic and barotropic components of the flow. Objective three includes monitoring the thermal and kinematic banding of the ACC, and obtaining descriptions of meso-scale features in the temperature and velocity fields near the Polar Frontal Zone, as well as obtaining additional information on energetic time and space scales.

The initial DRAKE 79 operation was a 27-day cruise of the *R/V Melville* beginning 11 January 1979 from Punta Arenas, Chile. Participants aboard this cruise, under the direction of Worth D. Nowlin, Jr., included scientists from the Instituto Hidrografico Naval de la Armada de Chile, Instituto Antartico Argentino, Servicio de Hidrografia Naval de Argentina, Texas A&M University, Oregon State University and the University of Washington. The operational objectives of this cruise were: to recover the moorings deployed in December 1977 from *AGS Yelcho*; to deploy the 1979 array; and to make series of XBT and hydrographic stations in order to describe the thermal and density fields in the region of the moored array.

Five moorings were set from the *AGS Yelcho* as a part of FDRAKE during December of 1977 (Nowlin *et al.*, 1979). Four of these moorings were recovered during the 1979 *Melville* cruise. One of the northern pressure gauge moorings failed to surface after the release was interrogated and triggered. Data recovery was excellent, yielding pressure records from both sides of the passage at 500 m depth and extending for a fourth year the current meter records from several levels near the main axis of the Antarctic Circumpolar Current in the Central Passage.

The 1979 moored array was designed to provide data which, in combination with hydrographic observations, will meet the scientific objectives of DRAKE 79 listed above. As seen in Figure 8, the array consists of 1) a main line of moorings extending across the passage from Cape Horn to Hero Bay in the South Shetlands and 2) a set of moorings to the west of this main line. The western set is placed near the central axis of the Circumpolar Current and will provide data for statistical and descriptive studies of meso-scale features associated with the current. The array contains current meters, temperature/pressure recorders, thermistor chains and bottom pressure recorders. The distribution of these instruments along the main line (with the exception of the bottom pressure gauges at 100, 500 and 2500 m on both sides of the passage) is shown in Figure 9. Current meters on both sides of the Polar Frontal Zone were equipped with a recently-redesigned conductivity cell proven to be more reliable than previous models. By combining these conductivity data with the temperature data, estimates of turbulent meridional fluxes of heat and salt will be possible.

Expendable bathythermograph observations made along the cruise track revealed the existence and northward migration of a clockwise rotating current ring. This ring, which contained a core of Antarctic Surface Water, had separated from the main axis of the Circumpolar Current and was located in the Polar Frontal Zone. The upper thermal structure observed on the first southward crossing of the passage is shown

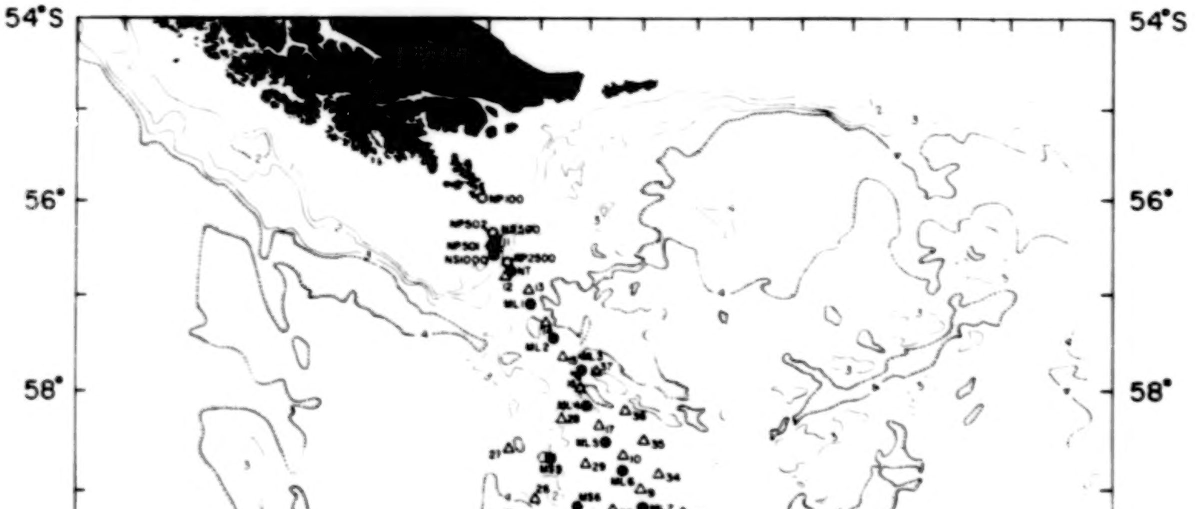


Figure 8. Locations of hydrographic stations and year-long moorings deployed during DRAKE 79 operations aboard *R/V Melville* from 11 January to 6 February 1979.

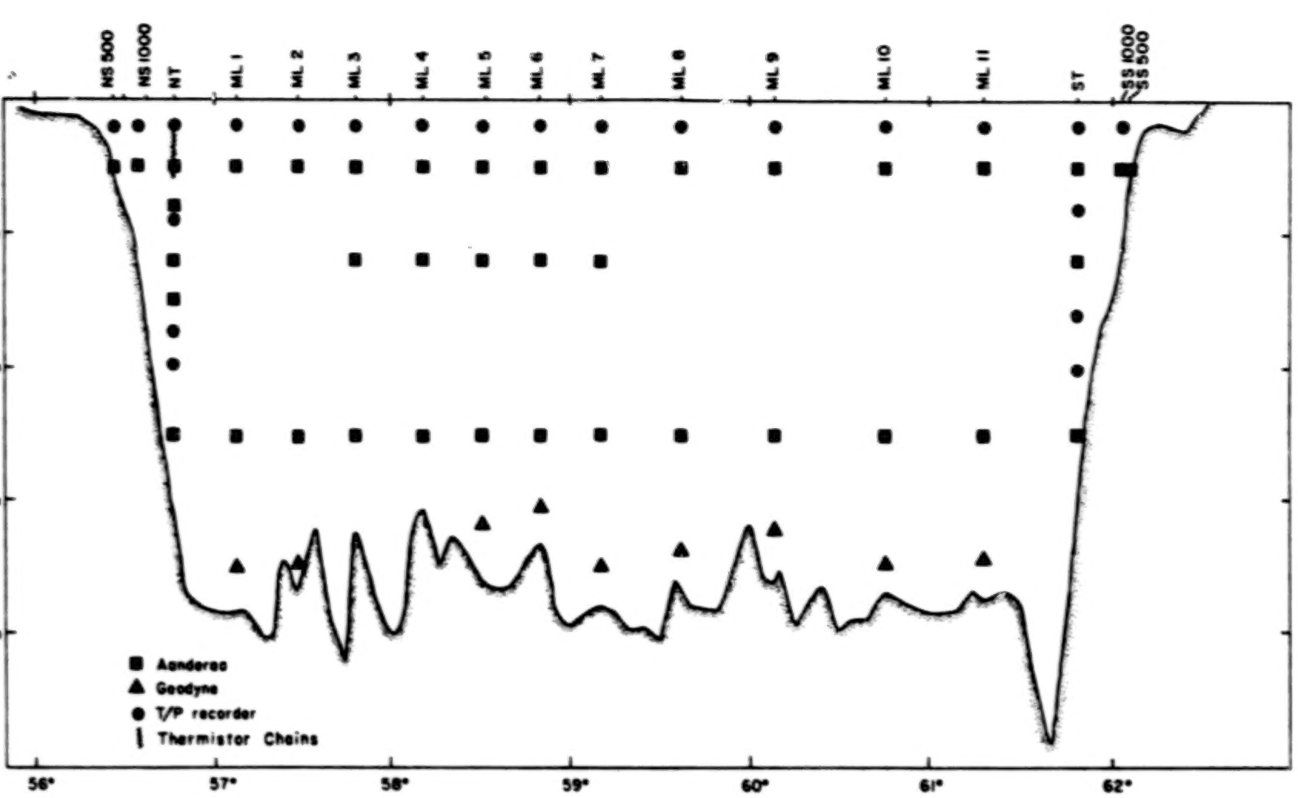


Figure 9. Vertical distribution of current meters, T/P recorders and thermistor chains along main line of DRAKE 79 array extending from Cape Horn to Hero Bay in the S. Shetland Islands.

in Figure 10. Indicated are the locations of the distinct surface water masses which are separated by bands of high eastward speed (Nowlin *et al.*, 1977).

The second operational phase of DRAKE 79 was carried out aboard the *AGS Yelcho* of the Chilean Navy. Cruise participants included scientists from the Instituto Hidrografico Naval de la Armada de Chile, Texas A&M University and Oregon State University. The cruise objectives were: first, to define the thermal and density fields during the austral fall in the region of the moored array of current meters, temperature/pressure recorders, thermistor chains and bottom pressure recorders deployed from the *R/V Melville*; and second, to add through-passage pressure measuring capability to the array by deploying a shallow water pressure gauge to the west of existing recorders at Isla Diego Ramirez.

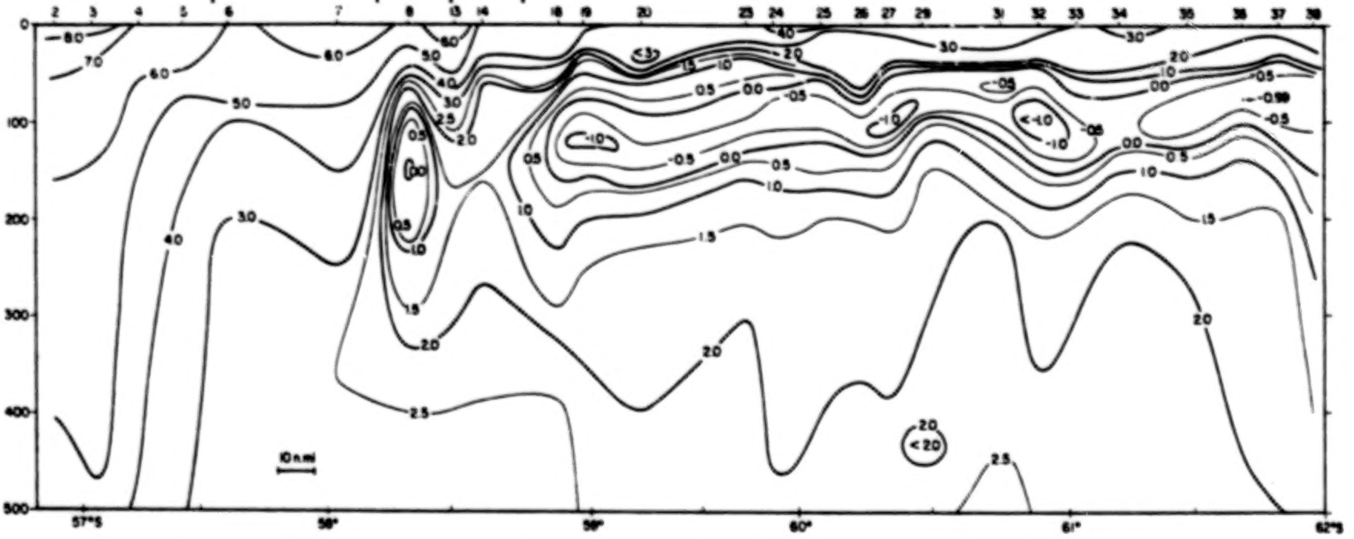


Figure 10. Temperature structure in upper waters as observed using XBT's along the main line during the cruise of the *R/V Melville*, 10 to 19 January 1979. Indicated are locations of surface water masses and of a clockwise-rotating ring within the polar frontal zone.

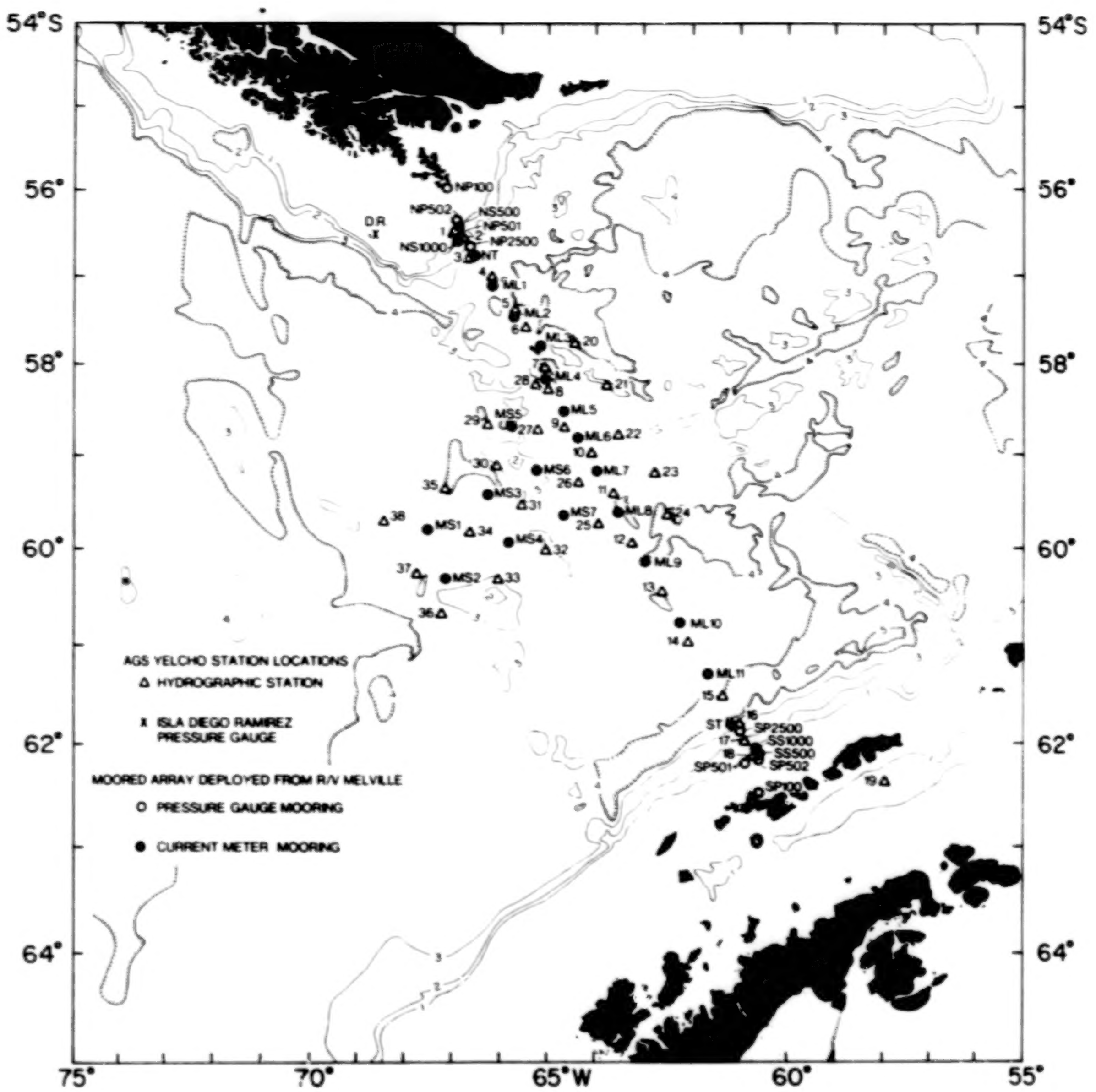


Figure 11. Hydrographic station positions and location of the Isla Diego Ramirez pressure gauge deployed during DRAKE 79 operations aboard *AGS Yelcho* (April/May). Also shown are the locations of year-long moorings from *R/V Melville* (January/February).

Operations aboard the *AGS Yelcho* were carried out in two legs. The first, beginning 9 April at Punta Arenas, Chile, consisted of two XBT sections and 19 hydrographic stations between Cape Horn and the South Shetland Islands along the main line of moored instruments (Figure 9). The current ring observed during the *R/V Melville* cruise did not appear in either of these XBT sections. During the second leg a shallow water pressure gauge was deployed at Islas Diego Ramirez, and 19 hydrographic stations accompanied by XBT measurements were conducted in the form of a grid encompassing the moorings to the west of the main line (Figure 11).

The third operational phase of DRAKE 79 was scheduled to be during September-October 1979 aboard the *R/V Atlantis II*. A hydrographic survey similar to that of the *AGS Yelcho* was planned, but because of delays in refitting the *Atlantis II*, this cruise was cancelled. Hopefully the *AGS Yelcho* will make late-winter XBT surveys over the DRAKE 79 array while resupplying Chilean Antarctic bases.

The last operational phase of DRAKE 79 is scheduled to be during January-February 1980 aboard the *R/V Atlantis II*. A hydrographic survey similar to that of the *Melville* and *Yelcho* will be made, and the moored array will be recovered.

During the operation period of DRAKE 79, the distribution of Southern Hemisphere winds will be obtained from the Australia Bureau of Meteorology and from the FGGE global wind analysis. Also, local winds in Drake Passage will be monitored by the Chilean Navy at a meteorological station on Isla Diego Ramirez in the northern Drake Passage. These wind data will be used to relate wind forcing to the current meter and pressure gauge data.

Arrangements have also been made with the Fleet Weather Facilities of the U.S. Navy to obtain data on the distribution of sea-ice in the Southern Hemisphere during 1979–80.

2.b. Interaction of Currents with Bottom Topography near Macquarie Ridge

The interaction of currents with bottom topography is one of the major subjects of ocean current dynamics. The purpose of this study is to carry out an experimental and theoretical study of a particular example of current-bottom topography interaction in the hope of being able to isolate and to identify the primary processes occurring during such interaction. In particular, the RIDGE (Ridge Interaction and Downstream Gradient Experiment) is an experiment being considered to study the physics of current-bottom topography interaction in the Antarctic Circumpolar Current. Such an experiment was recommended by the National Academy of Sciences in the report "Southern Ocean Dynamics—A Strategy for Scientific Exploration 1973–1983."

Consideration of plans for this experiment, as a part of ISOS, involved individuals from: the New Zealand Oceanographic Institute, Woods Hole Oceanographic Institution, Oregon State University, the University of Washington, the Pacific Marine Environmental Laboratory/NOAA and Texas A&M University. From their discussions the RIDGE Pilot Experiment evolved. A brief description of this experiment follows.

The cruise southeast of New Zealand by the *R/V Tangaroa* from 4–24 April 1978 marked the start of concentrated studies designed to investigate the Macquarie ridge/Campbell Plateau region south of New Zealand and the formation of Subantarctic Mode Water on the Campbell Plateau. The purpose of this initial experiment was to study the spatial and temporal variability of low-frequency motions and their effects on the mean circulation and to study the late-winter formation of Subantarctic Mode Water (McCartney, 1977) which is hypothesized to be similar to the formation of Subtropical Mode Water south and east of the Gulf Stream and Kuroshio (Worthington, 1959; Masuzawa, 1969).

Participating in the *Tangaroa* cruise were Harry Bryden from Woods Hole Oceanographic Institution, Ron Heath and Bruce Shakespeare from the New Zealand Oceanographic Institute, Dennis Root and Robert Still from Oregon State University, and David Spell from the Pacific Marine Environmental Laboratory.

During the cruise, 6 moorings equipped with Aanderaa current meters measuring temperature, pressure, current speed and direction were deployed: 5 in a cluster array near 49°30′S, 170°W on the abyssal plain of the south-western Pacific basin (Figure 12); and one at 51°10′S, 175°E on the slope of the Campbell Plateau. In addition, one drifting buoy provided by Dr. George Cresswell (Commonwealth Scientific and Industrial Organization, Cronulla, Australia) was launched at 50°30′S, 176°40′W and was tracked by satellite on its journey across the Pacific. Near the cluster array, 13 CTD (Conductivity/Temperature/Depth) stations to 1500 m depth were made to determine the spatial scales of the density structure. A large-scale survey of 26 CTD stations was made to define the broad scale density structure and associated circulation southeast of New Zealand.

The mooring on the slope of Campbell Plateau was equipped with 5 thermistor chains as well as 2 current meters to study the winter overturning of Subantarctic Mode Water and its relationship to the production of Antarctic Intermediate Water (McCartney, 1977). The CTD station near this mooring revealed a 100-m deep mixed layer with temperature and salinity values similar to those of Subantarctic Mode Water. That such a deep mixed layer was present in early autumn suggests that this is a region of active formation of Subantarctic Mode Water and that the formation may take place throughout the year rather than only during late winter.

Analysis of the CTD data showed that the cluster array was set in a strong frontal region where the dynamic height between 1000 m depth and the surface changed by 10 dynamic centimeters over about 15 miles. Because the CTD data in this region revealed significant amounts of subtropical water intermixed in subantarctic water, this front was probably the southeastwards extension of the Subtropical Convergence as located by Ridgway (1975). Within this front there was a pronounced tongue of water with a salinity maximum at a depth of about 150 m. The presence of such a tongue extending southwards from the Subtropical Convergence was first observed by Deacon (1937) and has more recently been analyzed by Heath (1976). The Subantarctic Front within which the thermistor chain mooring was located passes south of the cluster array.

The second operational phase of RIDGE was carried out aboard *R/V Knorr* from 12 November–9 December 1978 (Figure 13). Eighteen scientists from seven oceanographic institutions in the United States, Union of Soviet Socialist Republics, New Zealand and Australia participated on this cruise.

The first part of the cruise involved recovering the 6 moorings deployed in April 1978 from *R/V Tangaroa* (Heath *et al.*, 1978), deploying 1 site mooring to be recovered in early 1980, and taking a grid of conductivity/temperature/depth (CTD) stations about the moorings. All 5 moorings of the cluster array were recovered although the mooring line on each of moorings N and M was cut at about 1500 m depth so the top two current meters on each mooring were lost. All other current meters appear to have functioned normally. The CTD survey about the cluster indicated an eddy was present, albeit a weak one. CTD stations in this survey show both subtropical and subantarctic waters in vertical profile. This suggests that this region is one of active mixing of water masses. The sixth mooring near 51°S, 175°E was designed to study the seasonal evolution of surface mixed layers on Campbell Plateau, identified by McCartney (1977) as associated with the production of Subantarctic Mode Water. This mooring was recovered intact although the uppermost thermistor chain recorder was flooded (possibly due to a leak in the pressure sensor), and the middle thermistor chain had developed an oil leak.

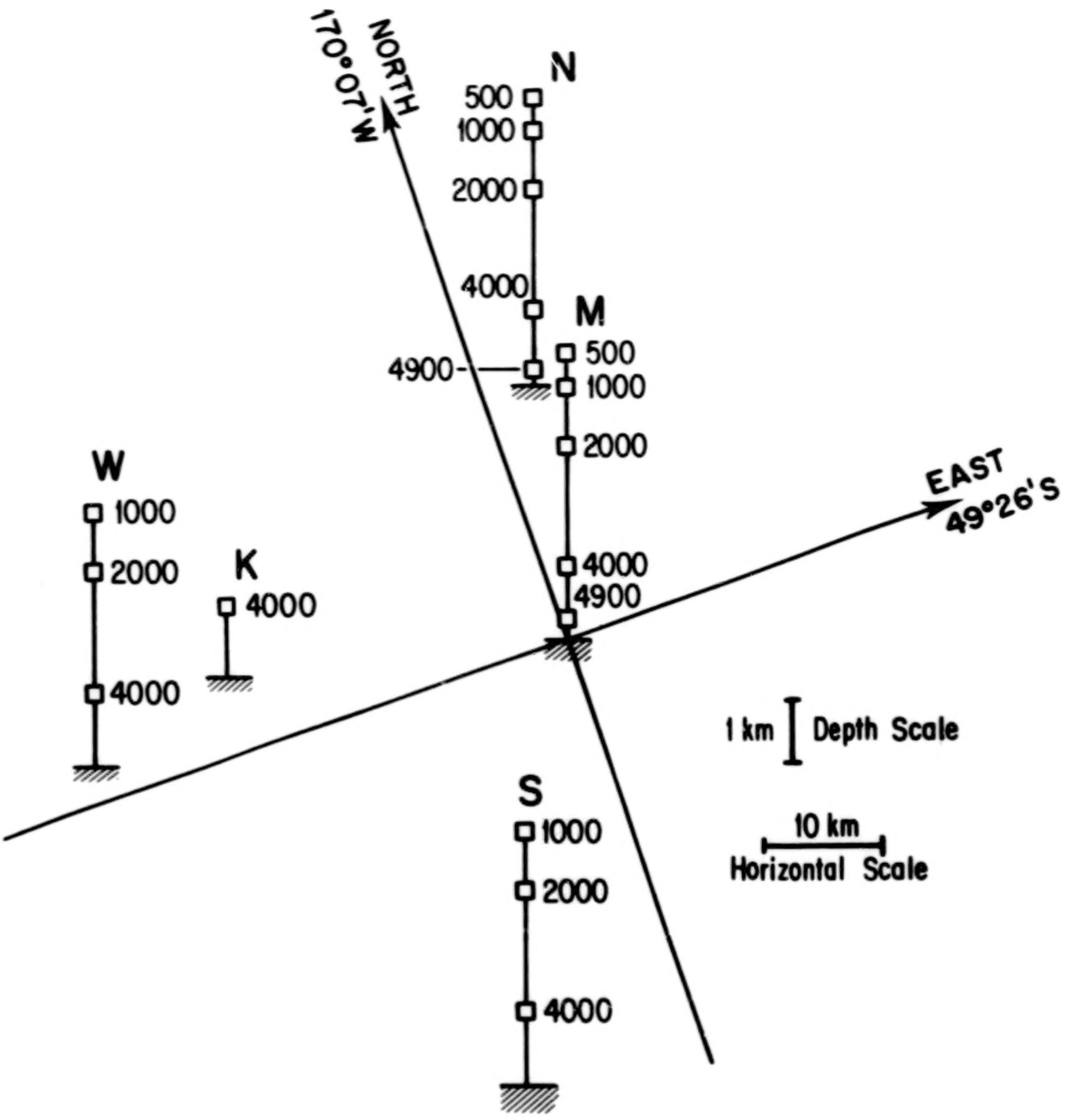


Figure 12. Positions of current meters in RIDGE array near 49°30'S, 170°W.

The remaining three thermistor chains and two current meters appear to have functioned normally. Interestingly, the CTD station near this mooring showed the water column to be well mixed in temperature but stratified in salinity.

In order to extend the time-series of current and temperature data to two years, a single mooring was deployed at 49°24'S, 170°30'W after the cluster array had been recovered. Initial analysis of the data from the RIDGE cluster array suggest that the interaction of the ACC with Macquarie Ridge generates large eddies which have important effects on the overall dynamics of the ACC. In particular, the observed eddies have large kinetic energy, transport heat poleward and transport eastward momentum northward away from the ACC.

Plans are now being made to: (1) recover the site mooring at 49°24'S, 170°30'W during April 1980; (2) describe the eddy characteristics in the RIDGE region; (3) compare the observations with infinitesimal amplitude baroclinic instability models; and (4) explore the relationship between observed eddies and predictions of finite amplitude instability models.

2.c. XBT Program of Upper Layer Monitoring

All three of the stated ISOS objectives require monitoring the temperature and salinity structures of the Southern Ocean. At present, the most cost-effective way to monitor upper-layer temperature structure is

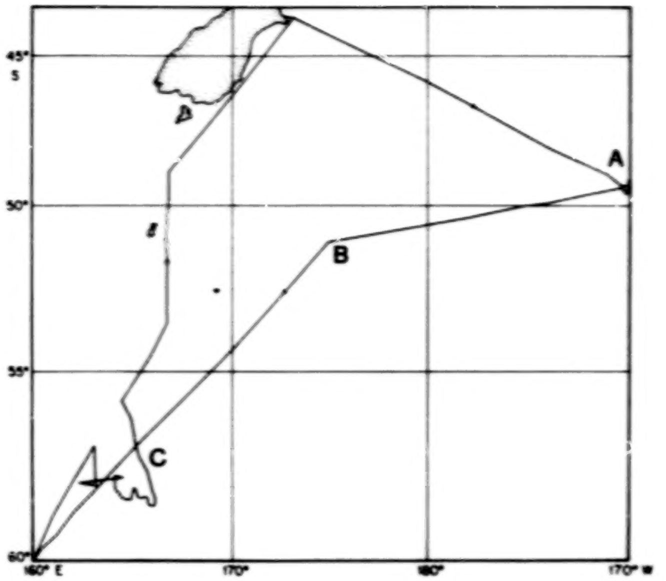


Figure 13. Cruise track of *R/V Knorr*, November 12–December 9, 1978. Position marked A is the site of cluster array of moorings and accompanying grid of CTD stations; B is the site of the single mooring with thermistor chains; and C is the site of the polar front study.

from "ships of opportunity" using expendable bathythermographs (XBTs). The supply vessels operating between various countries and Antarctica provide ideal platforms for this type of study.

Sections taken during the same months by different ships supply upstream and downstream coverage, offering a unique opportunity to study the spatial changes in the thermal structure of the ACC and to compare these changes to the available satellite meteorology. The repeated sections through the Drake Passage allow time series through part of the year for comparison with the current meter and meteorological data. The description and explanation of long-term changes of the summer thermal distributions south of Australia and New Zealand are another goal of the work there.

These vessels also take measurements of sea surface temperature and salinity. The surface temperature data are used to calibrate the XBT casts and also to provide reference data for high resolution satellite imagery to be taken in this region. The National Environmental Satellite Service agreed to provide Very High Resolution Radiometry (VHRR) data south of Australia and New Zealand at least once each week, and periodically every other day, during the 1977–1978 austral summer. Examination of existing VHRR imagery in the Southern Ocean indicates that cloudless periods do not occur very frequently during summer. Infrequent cloudless periods do, however, provide "snapshot" pictures of sea surface temperature which may be calibrated using the sea surface temperature data from the supply vessels. These pictures are used to describe the horizontal distribution of sea surface temperature and its relation to subsurface temperature structure monitored from supply vessels.

During the 1976–77 austral summer, XBTs were taken from supply vessels at 18 n.mi. (33 km) intervals along one east-west and 28 north-south sections. Most of the ships involved were supplying Antarctic land stations for Australia, Chile and the United States. Cruise tracks of vessels making XBT sections are shown in Figure 14.

The research vessel *Professor Zubov*, of the Arctic and Antarctic Research Institute of the USSR, sailed on 20 January 1977 from Wellington, New Zealand, on a 25-day USSR-USA cooperative cruise in the Southern Ocean south of Australia.

Due to prolonged severe sea conditions, much of the cruise was spent taking XBT casts under the direction of Dr. William Emery (University of British Columbia). XBT sections indicated the presence of an eddy at about 51°S and current meters were moored in this area.

Data collection continued during the 1977–78 austral summer. Arrangements were made to repeat the 12 XBT sections taken in the previous season in the Drake Passage by the *R/V Hero* and the Chilean vessel *AGS Yelcho*. South of Australia, the 8 XBT sections taken by *Nella Dan* and *Thalla Dan* were scheduled to be repeated this year. In addition, the South African vessel *Rsa* planned to take XBT casts on at least one crossing to the Antarctic south of South Africa.

Two U.S. icebreakers were again scheduled to collect XBT data on three north-south crossings of the circumpolar region south of New Zealand on the southbound leg. *USCG Burton Island* encountered three major frontal zones between New Zealand and the pack ice off Cape Andre. A coastal front of subtropical nature was encountered between 42°30′S and 45°S, tied to a topographic high off Christchurch. Enroute to Campbell Island, between 55°38′S and 55°40′S, the northern edge of a large meander in the Subantarctic Front was encountered. This meander is thought to be caused by flow over the Zacquani Aukland Rise System. A few days later *USCG Glacier* crossed a feature somewhat to the east which appeared similar in cross section but was a cold ridge rather than an eddy. A survey (incomplete due to high winds and seas) of the warm water beyond the meander indicated an extended filament of warm subantarctic water with a deep pool directly south of the meander. A cold core eddy was also found at 50°42′S.

The principal investigator for the project was Dr. William Emery (University of British Columbia) who collaborated with Mr. Hellmuth Sievers (Instituto Hidrografico de la Armada, Chile), Mr. Robert Edwards (CSIRO, Australia) and Mr. Stan Jacobs (Lamont-Doherty Geological Observatory, USA) in the project.

The ISOS XBT Program continued at a reduced level during 1978–79. As part of DRAKE 77, closely spaced XBT sections were made across Drake Passage in the vicinity of the current meter/pressure gauge array by the *AGS Yelcho* during supply missions to Chilean Antarctic bases during the austral fall and spring of 1978.

In 1979, the major emphasis has been on closely spaced XBT sections in support of the DRAKE 79 array. Sections have already been made during January-February 1979 by the *R/V Melville* and during

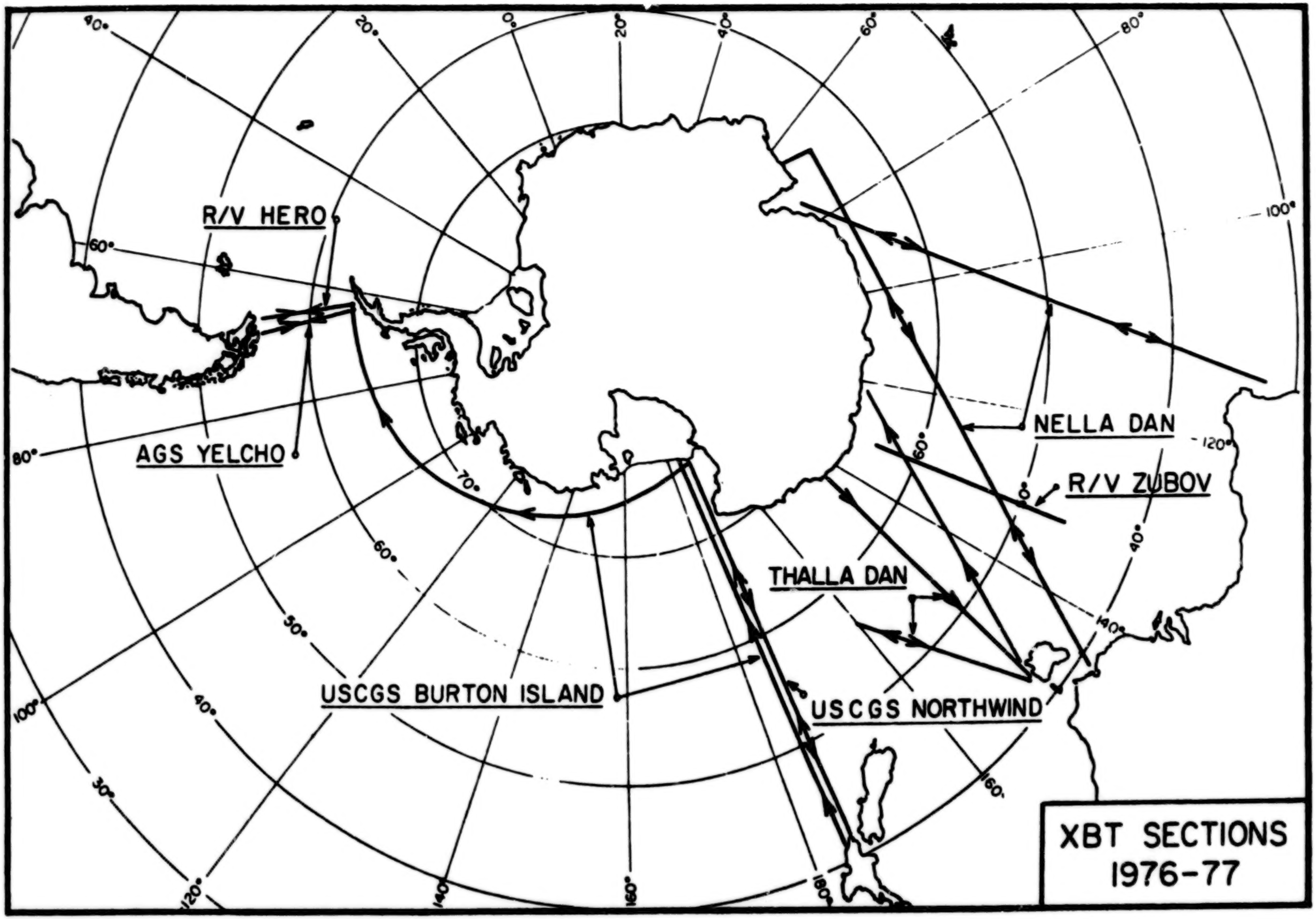


Figure 14. Cruise tracks of vessels from which XBT sections were obtained during the 1976–77 austral summer.

March-April 1979 by the *AGS Yelcho*. Additional sections will be made by the *Yelcho* during the early austral winter and again during the austral spring of 1979 while on supply missions to the Chilean Antarctic bases.

In addition to the XBT sections in the Drake Passage region, emphasis was also given to the region south of South Africa. Dr. J. R. Lutjeharms of the National Research Institute for Oceanology, Republic of South Africa, used XBTs obtained from the U.S. Navy (as part of FGGE) to make closely spaced sections between Africa and Antarctica. He has been using this data together with satellite infared imagery to look at structure of the ACC in this region.

The ISOS XBT Program will continue at about this same level during 1980.

2.d. Studies of the Polar Frontal Zone

The Polar Frontal Zone (PFZ) is the transition region between the surface waters of Antarctic and Subantarctic types. Antarctic Surface Water is characterized by a single intense subsurface temperature minimum layer in the summer. The Subantarctic Surface Water decreases monotonically in temperature with depth and has a nearly isohaline layer from 100 to over 400 m depth. The southern boundary of the Polar Frontal Zone is called the Polar Front.

Field studies of the Polar Frontal Zone began as a component of the FDRAKE experiment in the Drake Passage region during FDRAKE 75 and FDRAKE 76. During 1978, these studies were continued in the area south of New Zealand. Descriptions of these field activities, as well as some of the significant results of the Polar Frontal Zone studies, are presented below.

FDRAKE 75. *R/V Melville* made a section of 20 closely-spaced (5–10 km) STD stations across the PFZ in the western Scotia Sea. This pilot experiment was designed to more clearly define the scales of the thermohaline stratification across the front. A temperature section from the *Melville* data is shown in Figure 15.

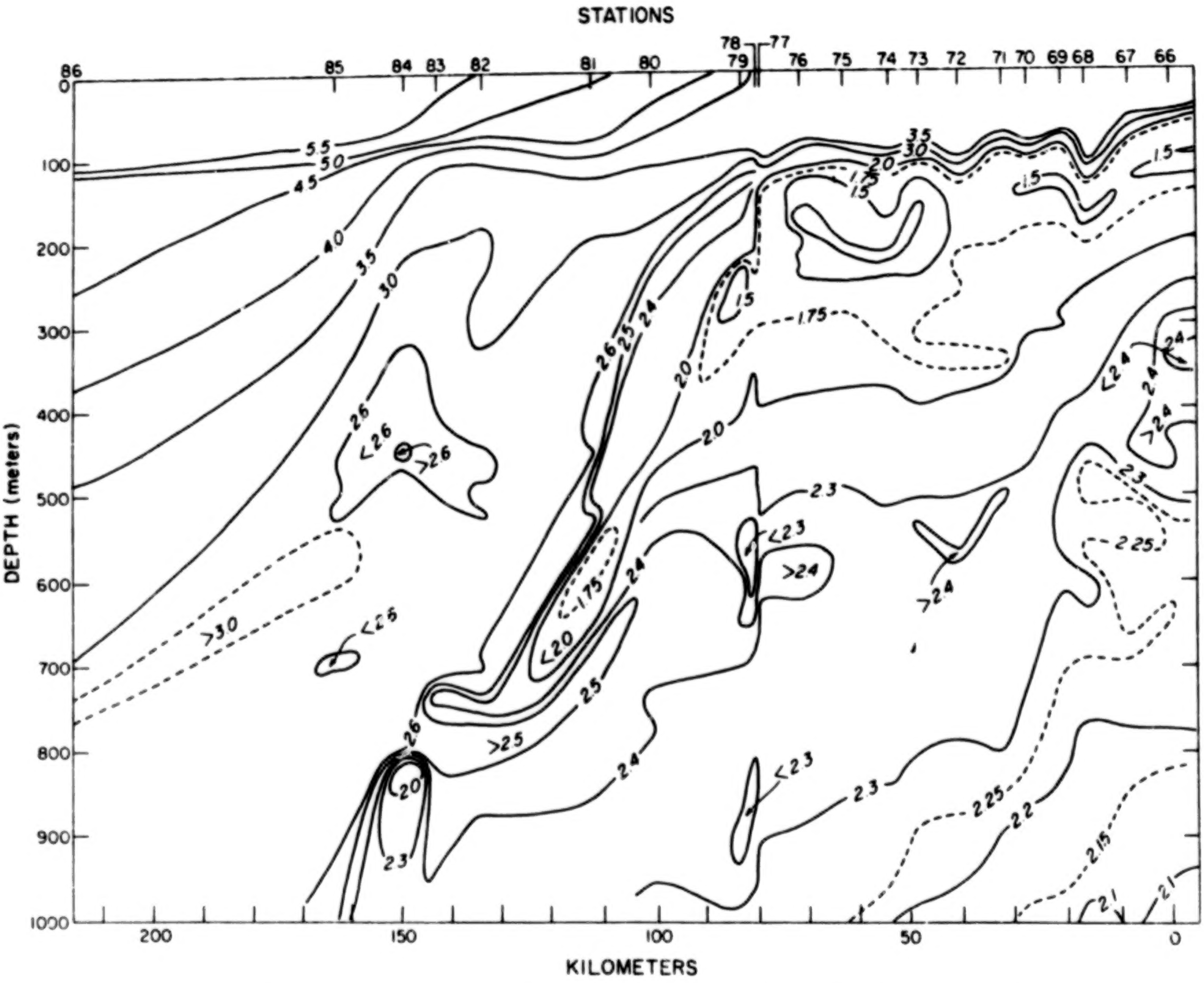


Figure 15. Temperature field across the Polar Front from STD data collected during March 1975 aboard *R/V Melville* in the western Scotia Sea.

Combined data from *Melville*, *Islas Orcadas* and *Conrad* (A. Gordon *et al.*, 1977) show a meandered PFZ with eddies of Antarctic water north of the Polar Front and of Subantarctic water south of the front.

1976 Field Program. The purpose of the Polar Front field program during FDRAKE 76 was to obtain measurements of the various scalar fields in the Polar Front with vertical and horizontal resolution surpassing previous studies and to obtain some direct measurements of vertical and horizontal velocities which might point out various dynamical processes related to the scalar variability. The cruise track is presented in Figure 16.

The velocity data were obtained with vertical current meters (VCMs) and a profiling current meter (PCM). VCMs are neutrally buoyant floats equipped with vanes to sense vertical motion of the water. Five VCMs were built and prepared at Woods Hole Oceanographic Institution (WHOI) and recorded 15 float days of good data during the experiment. The PCM is an Aanderaa current meter designed to slide down a CTD cable at 30 m/min and record pressure, current speed and direction. Walter Zenk from the Institut für Meereskunde, Kiel, West Germany provided this instrument. Using two reference buoys for relative velocity estimation, 19 absolute velocity profiles were obtained.

Various scalar fields were measured with the following instrumentation: (1) CTD: a WHOI/Brown CTD microprofiler was equipped with a sensor for continuous measurement of dissolved oxygen. A total of 101 stations were occupied. (2) XBT: 450 XBTs were collected for mapping of the thermal structure of the front and for statistical study of temperature interleaving in the frontal zone. An expanded scale system brought from Lamont by Dan Georgi was used for 300 of the stations. (3) Light Scattering: Gunnar Kullenberg from the University of Copenhagen obtained 48 stations in which the light scattering as a function of scattering angle was measured at discrete depths and continuous scattering at a fixed angle for depths between 0 and 1000 m. (4) Quanta Meter: Kullenberg also made 11 quanta meter stations. The quanta meter is essentially an electronic secchi disk. (5) Over 950 samples were processed for nutrients using an Auto-Analyzer operated by Clifford Dalm of Oregon State University. Of these, 240 were surface samples collected aboard the *AGS Yelcho*. (6) Isotope analysis: 28 samples were drawn for Tritium/Helium^3 and 78 for O^{18}/O^{16} analysis. The former will be done by William Jenkins at WHOI and the latter through Louis Gordon at Oregon State University. The optical and chemical studies provided additional data for water mass identification and composition.

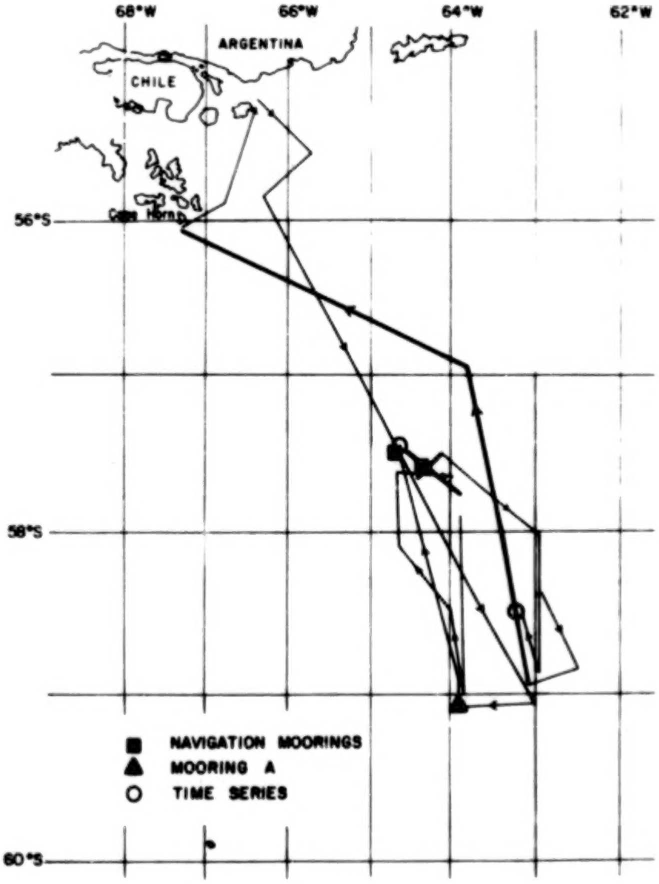


Figure 16. The cruise track of the *R/V Thompson* during the survey of the Polar Frontal Zone. The Polar Frontal Zone was encountered in the vicinity of 58°S.

In addition to the above, a subsurface mooring was recovered containing three vector averaging current meters belonging to Pacific Marine Environmental Laboratories (NOAA) and two 50-m thermistor chains from the Institut für Meereskunde, Kiel. A discussion of this data has been jointly prepared by Hayes and Zenk (1977). During the course of the four-week *Thompson* Leg III study, *Yelcho* assisted in defining the meso-scale structure of the Polar Front. A meander in the Circumpolar Current/Polar Front was observed to pinch off forming an eddy of cold antarctic water which then drifted to the northeast in the Circumpolar Current (see below). Patterson and Sievers (1976) and Joyce (1976) have prepared more complete summaries of the *Yelcho* and *Thompson* Leg III field work. A comprehensive Leg III cruise report (Joyce *et al.*, 1976) has been prepared which includes discussion of the preliminary data. Two modes of transfer of heat and salt have been identified (Joyce and Patterson, 1977a) as operative in the Polar Front: mesoscale eddies and interleaving. A brief description of these processes follows:

Mesoscale Variability. Over a five-week period during FDRAKE 76, a meander in the Circumpolar Current was observed by Joyce and Patterson (1977b) to grow and pinch off a cyclonic ring of Antarctic water to the north of the PFZ. (See the sequence of locations of the Polar Front from three synoptic mappings shown in Figure 17.) This ring subsequently drifted northeast into the Scotia Sea. Hydrographic measurements obtained with a conductivity/temperature/depth (CTD) recorder show that most, if not all, of the water column was involved in the equatorward ejection of the cyclonic ring. We know neither the ultimate fate nor the frequency of formation of such cyclonic rings and their anti-cyclonic counterparts, although the possibility exists of remote tracking from satellites.

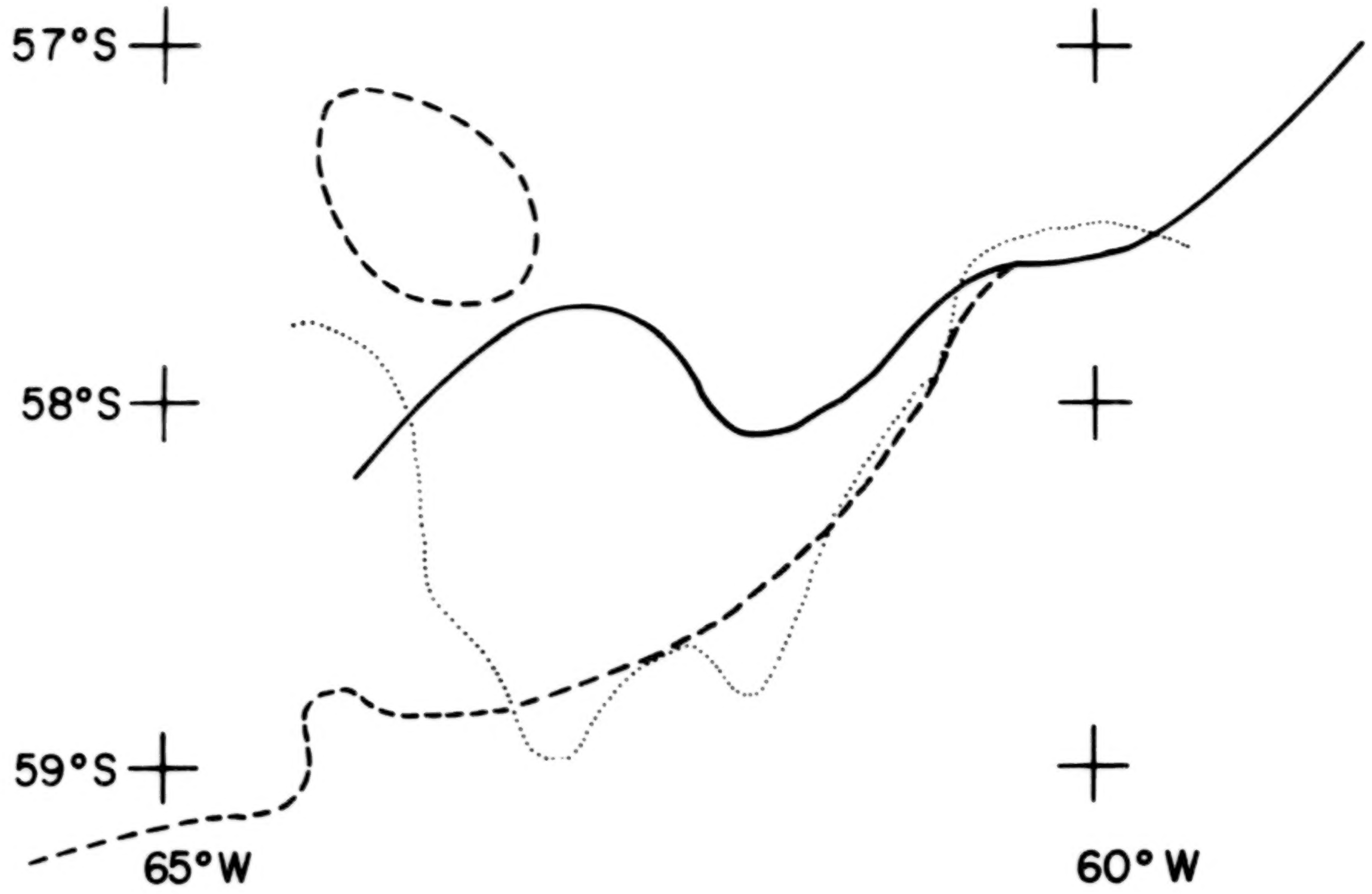


Figure 17. Three synoptic structures of the polar front showing the evolution of the cold water eddy according to the XBT observations of the Chilean vessel *Yelcho* in 1976. The solid line indicates the position of the polar front for 28 February to 7 March, the dotted line for 24 March to 28 March, and the dashed line for 28 March to 5 April.

Interleaving. The CTD data presented in Figure 18 shows features responsible for the second mode of transfer across the PFZ, small scale interleaving. The temperature, salinity and dissolved oxygen fields show multiple inversions with vertical scales of 10–100 m while the density (σ_t) is comparatively monotonic with depth. This indicates that the temperature and salinity variations compensate each other in such a way that static instabilities in density are essentially absent. Closely spaced stations are necessary to map intrusions statistically. The entire PFZ is filled with these structures, each of which has some varying fraction of Antarctic and Subantarctic water properties. A description of this phenomenon in the Southern Ocean has been made by D. Georgi at Lamont. One might imagine the intrusions acting as a great "heat exchanger" increasing the surface area of contact between different water masses and thereby enhancing the smaller-scale mixing. In order to maintain the interleaving in a statistically steady-state, cross-frontal exchange proportional to (a) the intensity of interleaving, and (b) the rate of destruction (by vertical exchange) of each "leaf" is necessary.

Joyce *et al.* (1978) note that, within the Polar Frontal Zone, water masses interleave with characteristic vertical scales of 50–100 m. These intrusions are horizontally anisotropic, being elongated in the along stream direction and constrained primarily to the upper 800 m of the front. The thermohaline variability was associated with nearly isentropic advection of different water masses across the front.

1978 Field Programs. From 12 November to 9 December 1978, field study of the Polar Front continued in the region south of New Zealand aboard the ***R/V Knorr***. Under the direction of Dr. Terrence Joyce of Woods Hole Oceanographic Institution, the shipboard program centered around CTD measurements with XBTs and vertical current meters (VCMs).

After locating the Polar Front, determining its orientation from four crossings, and taking a CTD section principally across the axis of the front, two neutrally buoyant floats (called VCMs) were deployed at 215 and 630 m depths on the warmer side of the front so that a water parcel could be followed for several days. (A third float was lost during a recovery attempt as a result of difficulty in maneuvering the ship near the float in rough seas.) As the floats were tracked, CTD work consisted of stations over the floats, two-yo profiles (described below) around the shallower float, VCM 5, and stations poleward and equatorward of the float track to bracket the water masses in the front. The water mass structure of the area is typified by a minimum temperature (T_{min}) region near 200 m depth and by interleaving structures

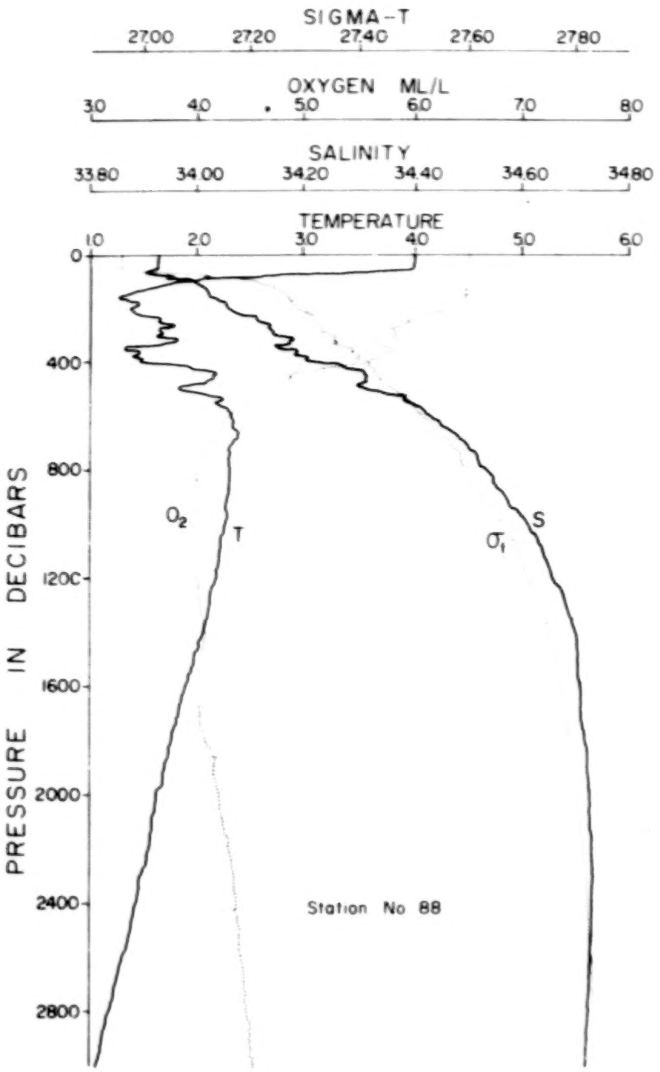


Figure 18. Continuous temperature, salinity, and oxygen profiles of CTD station #88.

which are more prominent on the warmer side of the front. During the four-day period VCM 5, which was within the T_{min} layer, moved southward and then eastward with a speed of 50–70 cm/sec. Four tow-yo profiles of approximately four hours duration were made near the float. In this operation, the CTD was successively lowered and raised from 50 to 500 m depth as the ship steamed at two knots. These stations were designed to examine differences in variability of interleaving water masses in along-front and cross-front directions. After two days, the deeper float was substantially behind the shallower float so it was recovered and redeployed at 430 m near the shallower float to provide an estimate of velocity shear. This study indicated that interleaving layers can be followed over horizontal scales of 5 km, and it is planned to quantify the differences between the scales of along-frontal and cross-frontal interleaving layers and compare with results in Drake Passage described by Joyce *et al.* (1978).

After the Polar Front study, a CTD section was taken from 60°S, 160°E onto the Campbell Plateau, across the Plateau and Snares Gap onto the continental shelf just south of the southern coast of New Zealand. This section should provide a description of the nature of water which flows onto Campbell Plateau from the west and which must evolve into Subantarctic Mode Water on the plateau. This section should complement the survey of waters on the plateau by McCartney during the two months prior to this cruise.

Significant Results. The research program has concentrated on upper water mass exchange across the Polar Front. Two processes have been identified as operative (in the Drake Passage at least): ring formation and interleaving. Gordon and Georgi have contributed to the study of interleaving leading up to the FDRAKE 76 field program. A conceptual model for the cross-frontal fluxes has been developed, and Joyce *et al.* (1978) have made crude estimates of the Southern Ocean wide heat and salt fluxes. They estimate that interleaving can account for 10 and 60 percent, respectively, of the poleward fluxes of heat and salt necessary to balance surface inputs south of the Polar Front. In short, interleaving must be significant in the thermodynamic balance of the Southern Ocean. One curiosity which has arisen is that interleaving produces a negative density diffusivity, tending to increase poleward density gradients. This process might explain why water mass boundaries are also density fronts.

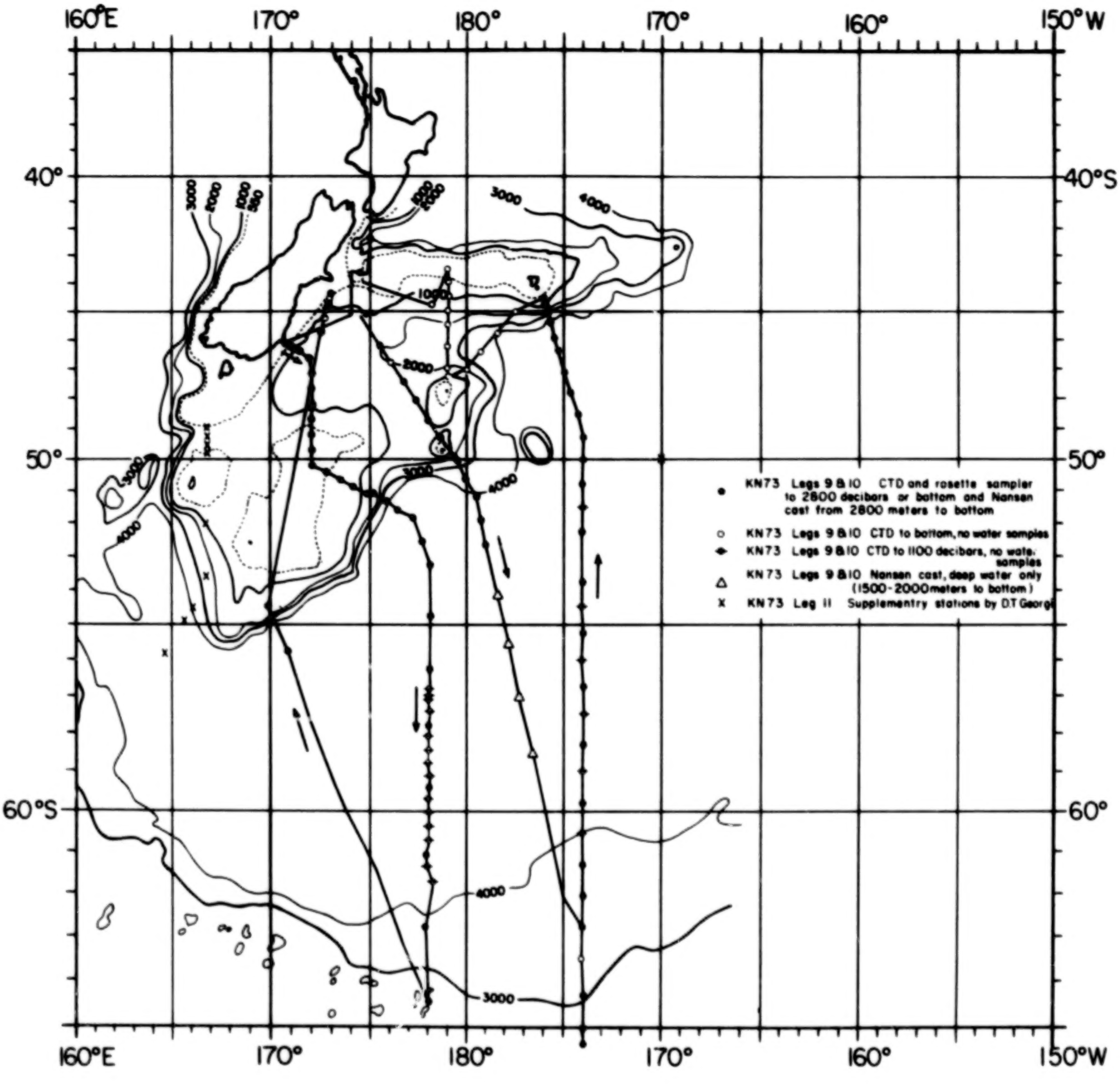
The Polar Frontal work has borrowed from (and contributed to) other ISOS research. An example is the modification of the shallow S_{min} layer due to cross-frontal exchanges. This problem is being investigated with a process-oriented model as well as an advective-diffusive numerical model. This study should touch closely upon McCartney's work in Subantarctic Mode Water. Also, a possible mechanism has been suggested whereby density steps in the ACC might be associated with water mass boundaries. This multiple-jet discovery is one of the principal results to come out of the large-scale hydrographic program.

2.e. Water Mass Renewal and Circulation of Subantarctic Zone

A new phenomenology of water mass formation and circulation in the subantarctic zone has emerged from McCartney's studies of the historical data set (McCartney, 1977). This background is discussed in section 4.b. Two field programs are planned based on the results of these studies.

New Zealand Sector. In the documentation of the longitudinal variation of 18°C water-like family of Subantarctic Mode Waters (McCartney, 1977), a distinct break in the otherwise mostly smooth east-west trend of mode water temperature and salinity characteristics was found at New Zealand. West of New Zealand the modes are predominantly warmer than 8.3°C and saltier than about 34.57‰. East of the Chatham Rise east of New Zealand the modes are clustered around 7.0°C and 34.45‰. In between, flow of the subantarctic zone is diverted southward by New Zealand. There is very little hydrographic data south and southeast of New Zealand to use for developing a picture of the circulation of the region. What little there is suggests that the Subantarctic Front position is topographically controlled, and associated with the 1000–3000 m depth part of the flank of the plateau. North of the front in the subantarctic zone, the flow streamlines may diverge over the plateau, with a resultant increase in the ratio of water column surface area to area to advection time. This would allow an increased air-sea exchange compared to other parts of the subantarctic zone and account for the comparatively large west-east gradient in SAMW properties in this sector.

The intent of the field program that McCartney carried out from 18 September–5 November 1978 from the *Knorr* was to obtain a late winter snapshot of the hydrography of this region. The cruise track is shown in Figure 19. This track allowed determination of the relationship of the Subantarctic Front to the Campbell Plateau-Chatham Rise complex. The convective overturnings were mapped. An evolutionary perspective was provided by the site mooring near 51°S, 175°E. It was instrumented with current meters at 350 and 980 m (50 m off the bottom), and with 5 thermistor chains spanning the water column from 130 to 685 m. At launch time the mixed layer was 140


160°E
170°
180°
170°
160°
150°W
40°
40°S
50°
50°
60°S
60°
3000
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4000
3000
4000
1000
2000
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4000
3000
4000
4000
3000
KN73 Legs 9 & 10 CTD and rosette sampler to 2800 decibars or bottom and Nansen cast from 2800 meters to bottom
KN73 Legs 9 & 10 CTD to bottom, no water samples
KN73 Legs 9 & 10 CTD to 1100 decibars, no wate. samples
KN73 Legs 9 & 10 Nansen cast, deep water only (1500-2000 meters to bottom)
KN73 Leg II Supplementry stations by D.T Georg

Figure 19. Cruise track of *R/V Knorr* cruise 73, Legs 9, 10, 11, September 18-November 5, 1978. Water samples taken by Nansen bottle or rosette sampler at 127 stations were processed for salinity, dissolved oxygen, silicate phosphate, nitrate, nitrite, and ammonia. Additional samples were taken at some stations for Tritium/Helium studies by Dr. Jenkins (Woods Hole Oceanographic Institution).

m thick, and about .2°C colder and .25‰ less saline than the "old" mode water underneath it. As the fall and winter cooling proceeds the 10-m spaced thermistors hopefully monitored the progressive deepening of the mixed layer. The *Knorr* survey established a horizontal context for analyzing the mooring data. Meteorological data routinely collected at Campbell Island, some 430 km west-southwest of the mooring, will allow correlation of events observed in the mooring records with possible meteorological events, e.g., cold, dry wind outbreaks from the southwest.

In view of the dearth of data southeast of New Zealand, the *Knorr* sections were extended as far to the southeast as seasonal ice conditions permitted, with stations made to the bottom throughout. One topic of analysis of this data set will be the cross-over of the southwest Pacific basin by Antarctic Bottom Water. This was inferred by McCartney on the basis of existing hydrographic sections along 170°E and 43°S. At 170°E, the coldest water is piled up on the northern flank of the zonally trending mid-ocean ridge, at about 62°S. At 43°S the coldest water is pilled up on a classic northward flowing deep western boundary current at the base of the Chatham Rise, at 160°–168°W.

W. J. Jenkins of Woods Hole collected Tritium/Helium^3 samples in concert with McCartney's program. The immediate focus of this program is on Tritium/Helium dating for SAMW and AAIW, as well as primordial Helium^3 measurements in the deep and bottom water. The AAIW dating will be particularly useful in connection with McCartney's non-circumpolar AAIW formation hypothesis, which indicates the AAIW south of New Zealand as being the oldest of that found within the circumpolar subantarctic zone.

A preliminary picture of the deep circulation southeast of the plateau may be inferred from the potential temperature distribution at 3000 m (Figure 20) from the Leg IX and X data, as well as other historical data. The coldest water is found as an extension to the northeast paralleling the southeastern flank of the plateau, although distinctly removed from being directly "piled up" against the plateau base. The switchover of the isotherm pattern from predominantly zonal south of 56°S, the southern extremity of the plateau, to the predominantly meridional pattern north of this latitude is striking. The bottom water temperatures match this 3000-m distribution, with coldest values southeast of the Chatham Islands being about .04°C warmer than southeast of the Antipodes Islands.

Drake Passage Region. The McCartney hypothesis for Antarctic Intermediate Water is discussed in some detail in section 4.b. The question of the relative importance of annual mean horizontal fluxes of heat and salt from the SAMW to the cold, low salinity antarctic zone compared to the annual average air-sea heat loss and excess of precipitation over evaporation in the subantarctic zone is a difficult one to address. Estimates of the magnitude of the former are emerging from the work of Joyce and of Bryden. For the latter, heat exchange estimates can be made using bulk aerodynamic formulae, but the data are extremely limited. For the evaporation-precipitation difference, there are few data to be used in direct calculations, and instead indirect evidence inferred from the zonal mean climatology have to be used.

The importance of the homogenization of the water column by vertical convective overturning can be directly assessed by a field experiment. The questions that McCartney and Georgi have proposed to address in late austral winters and early springs of 1979 and 1980 are mainly directed at: (1) What is the coldest type of SAMW formed in the South American sector of the subantarctic zone? (2) What is the volumetric distribution of the newly renewed SAMW in temperature-salinity space? (3) At what associated SAMW temperature does the geostrophic velocity field indicate a bifurcation between modes that turn north off Chile as part of the South Pacific anticyclonic gyre and those that pass through the Drake Passage into the South Pacific? (4) What volume flux of SAMW into the South Atlantic is indicated by the 1979 late winter hydrography combined with the DRAKE 79 current meter array? (5) Is there a seasonality in the properties of the SAMW moving through the Drake Passage, and if so, can the advection be quantified? (6) Can the result of (4) be combined with an estimate of the eastward flow of SAMW south of New Zealand obtained in the 1978 experiment, to quantify the fluxes necessary to modify the warmer, saltier New Zealand sector modes, to the cold, low salinity modes of the Drake Passage? (7) How do the proportion of the SAMW and Polar Frontal Zone waters passing through the Drake Passage relate to the waters carried north with the Falkland current to enter the South Atlantic gyre at the Falkland Brazil confluence?

It is proposed to address these questions with two different program components. The McCartney/Georgi proposal covers a late winter/early spring hydrographic survey of the southeast Pacific, Drake Passage, and southwest Pacific. This two-leg, 70-day survey aboard the *R/V Atlantis II* during 1980 will address questions 1, 2, 3 and 7. The second component is included within the DRAKE 79 moored experiment. Moorings on the main line across the passage were instrumented with temperature pressure recorders at 200 m, in addition to the temperature, conductivity, and current measurements at 500 m. The heavily instrumented transport mooring at 3000 m on the northern side of the passage has four thermistor chains spanning the water column from 200 m to 600 m, as well as temperature, pressure, conductivity and current measurements at 500 m. These instruments will address questions 4 and 5. Specifically, year-long temperature measurements at a single point, in 500 m of water on the north side of the Drake Passage has an intriguing cycle. At the beginning of austral winter, the 500-m temperature was about 4.8°C. During the winter this temperature decreased to an end of winter minimum of about 3.8°C. This represented simple vertical motion of the main thermocline, which would imply a seasonal change of baroclinic transport. On the other hand, the 4.8°C

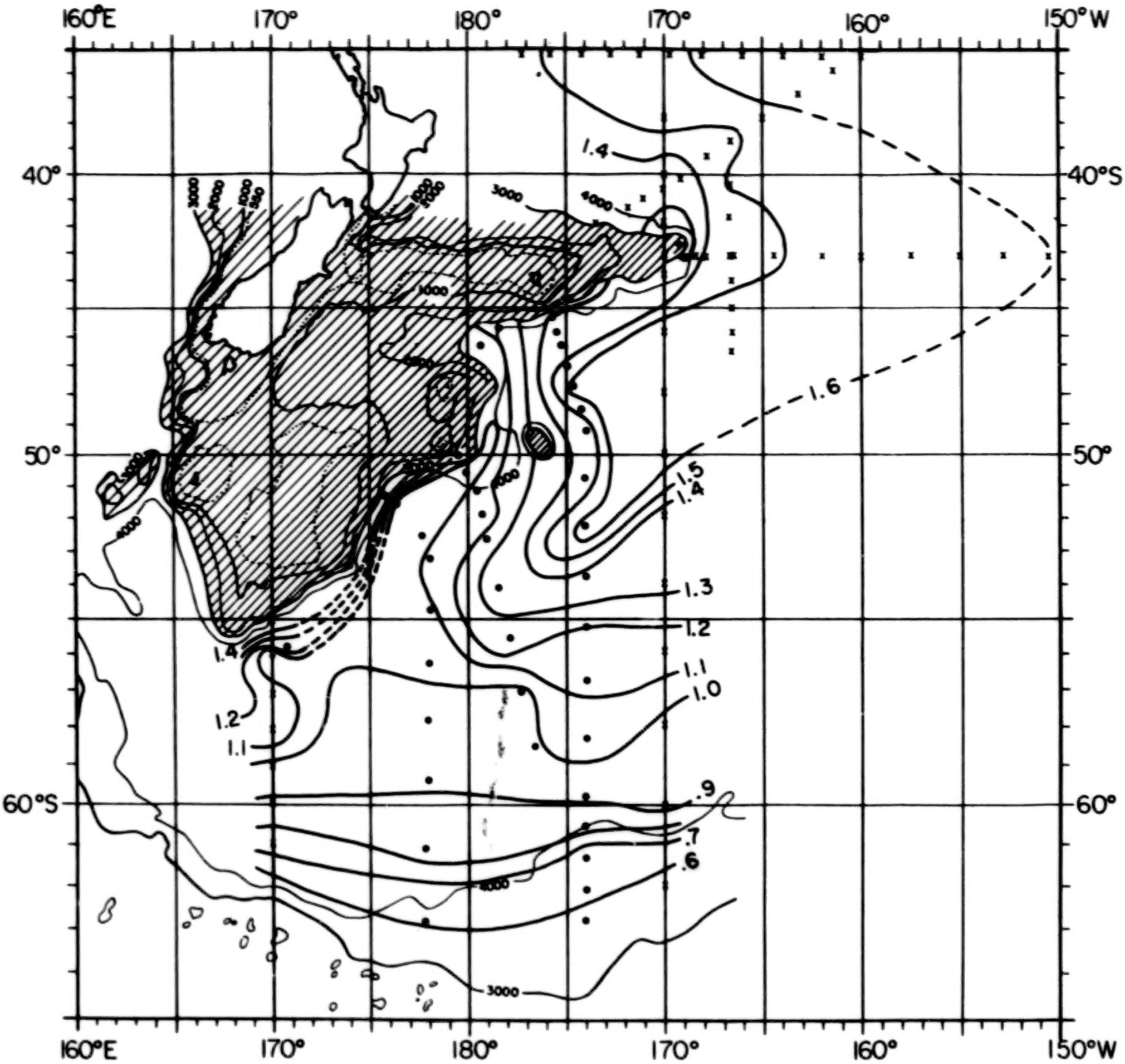

Figure 20. Potential temperature at 3000 meters, using data from *R/V Knorr* cruise 73, legs IX and X, combined with historical data to the west, east and north.

water could have been one-half year old SAMW from farther west that advected into the passage, while the steady decline to 3.8°C could have been a result of air-sea modification of the mode water by convective overturning. The vertical instrumentation of the DRAKE 79 array should give more information about these processes.

Addressing question 6 will be William Jenkins' program of Tritium/Helium^3 sampling which will be of particular use in contrasting the AAIW of the New Zealand sector to that in the South American sector. Primordial Helium^3 measurements will be made in the deep water where they are expected to be of much use in contrasting old deep water (high Helium^3) to young deep waters (low Helium^3).

2.f. Pilot Program of Winter Measurements under Sea Ice

The pilot program of winter measurements under sea ice was set up by Drs. Henry Crew and Victor T. Neal (School of Oceanography, Oregon State University) to develop the techniques necessary for long-term monitoring of physical oceanographic processes under the sea ice. The work carried out in McMurdo Sound in September 1974 demonstrated that oceanographic data can be obtained from ice stations during the austral winter. Repeated vertical profiles of temperature and horizontal currents as well as standard hydrographic data were obtained. The currents were weak and mostly barotropic. Conventional hydro-

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graphic measurements indicated little significant structure. However, the repeated high resolution (instrument resolution to better than .001°C) temperature measurements revealed transient step-like features in vertical profiles. These features were typically 2 to 4 m thick.

2.g Southern Ocean Lagrangian Observations

The long-range scientific objectives of this research program are to determine:

1. The large horizontal space and time scales of the surface Antarctic Circumpolar Current;
2. The characteristics of the wintertime circulation of the surface Circumpolar Current.

These goals are qualitative. They contribute principally to the ISOS long-range goals of determining:

1. The interaction of the Circumpolar Current System with other oceanic regions and atmospheric circulation;
2. The kinematic and dynamics of the ACC frontal zones.

The Southern Oceans Lagrangian Observations (SOLO) program has been funded at a modest level since November 1974. During the period of November 1974 to November 1977, the major efforts of this program were toward the technical development of a buoy-drogue system which would be able to survive the severe conditions of the antarctic. In addition, considerable efforts were made toward developing the techniques necessary for interpreting the drifter data.

The SOLO Pilot Program began with the development of five satellite-tracked drifters during late December 1977 from the *USCG Burton Island*. Two U.S. icebreakers, the *USCG Burton Island* and the *USCG Glacier*, were scheduled to collect XBT data on three north-south crossings of the circumpolar region south of New Zealand. Enroute to Campbell Island, along 170°E longitude between 55°38′S and 55°40′S, the northern edge of a large meander in the Subantarctic front was encountered. A satellite-tracked drifter was launched in the center of this meander. A second drifter was deployed in the meander's southern front at 57°40′S. Data indicated an extended filament of warm Subantarctic water directly south of the meander. The track of a drifter launched near the center of the warm pool indicated that the filament was not closed off. A cold core centered near 59°42′S was marked with a drifter. The fifth drifter was deployed further south in the Antarctic water with subsurface temperature minimum.

These drifters had sensors to measure sea surface temperature, battery voltage and drogue line tension. One drifter failed completely on the first day and another terminated transmission after 13 days. The remaining three gave substantially longer records of position (75, 119, 193 days).

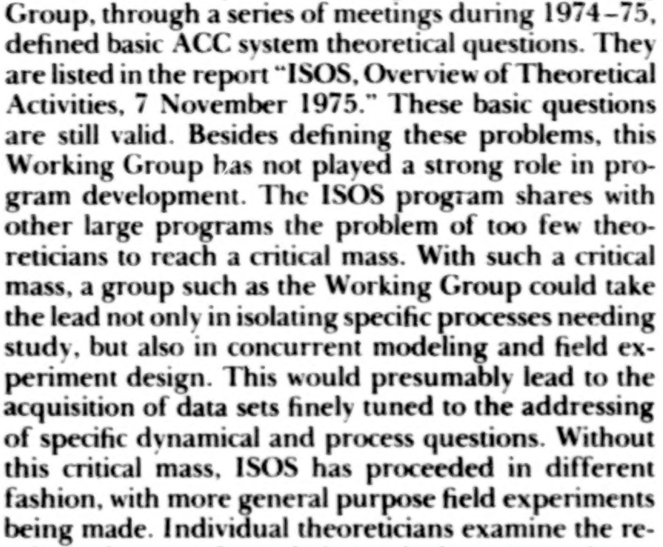
The drifter trajectories show a range of horizontal space scales exist within the surface Circumpolar Current. Eddy motions of scale 40 km (1 week) to meander features of 250 km (1 month) are evident in the data. The smoothed trajectories also agree with historical relative dynamic topography (Gordon *et al.*, 1978). Only one drifter continued transmission into the austral winter. Conclusive remarks concerning wintertime surface circulation can not be based on this alone.

For the 1979–1980 period, data from the Southern Hemisphere deployment of FGGE drifters will be utilized.

3. Supporting Theoretical and Laboratory Studies

3.a. Overview

At the beginning of the ISOS program, a Working Group on Theoretical and Special Process Studies was established by Drs. James Luyten of the Woods Hole Oceanographic Institution and D. James Baker, Jr. of the University of Washington. This Working Group, through a series of meetings during 1974–75, defined basic ACC system theoretical questions. They are listed in the report "ISOS, Overview of Theoretical Activities, 7 November 1975." These basic questions are still valid. Besides defining these problems, this Working Group has not played a strong role in program development. The ISOS program shares with other large programs the problem of too few theoreticians to reach a critical mass. With such a critical mass, a group such as the Working Group could take the lead not only in isolating specific processes needing study, but also in concurrent modeling and field experiment design. This would presumably lead to the acquisition of data sets finely tuned to the addressing of specific dynamical and process questions. Without this critical mass, ISOS has proceeded in different fashion, with more general purpose field experiments being made. Individual theoreticians examine the resultant data sets from their particular perspective to obtain direction for modeling activities. Thus the flow of ideas in ISOS has followed this scheme:



The solid lines show the main idea flow lines and feedback paths in ISOS. The only main link between the parallel tracks occurs at the interpretation end. The dashed lines show the less well developed flow lines and feedbacks that have been more recently developing. The dotted line is the least well developed link: sharply defined theoretical principles and a rationale for designing field experiments to test theoretically predicted dynamical balances and particular processes.

There has been a common thread in the various theoretical studies supported by ISOS: the role of topography in the global balances of the ACC system. Drs. M. S. McCartney and H. L. Bryden have begun to examine the possibility of a field experiment directed at the specific problem of estimating the pressure torque exerted by a bottom topographic feature on the ACC. A small current meter mooring array was set in April 1978 in what may be a Rossby wake regime downstream of the Campbell Plateau south of New Zealand. This will give scale information valuable for planning a future pressure torque/momentum flux experiment in this sector. Discussion of this experiment will continue in ISOS; it is likely that the actual experiment is several years off.

A shift from the topography/global balance emphasis is occurring. The data from the first year-long study were empirically analyzed by Dr. H. Bryden (1978) to show the potential importance of baroclinic instability in the passage. Dr. R. deSzoeke, aware of Bryden's work, had initiated a theoretical study to isolate and study processes of instability as revealed by the data. In addition, Dr. C. Fandry, of Monash University, visited OSU for one year in order to look at Southern Ocean models in the light of the ISOS data.

An opportunity for a major step forward from this nucleus of studies will occur the end of the ISOS field activities. Plans now call for a special Chapman Conference of the American Geophysical Union on Southern Ocean Dynamics during 1981 where a full presentation of the ISOS data to a highly qualified group of both theorists and experimentalists will be made. Hopefully this meeting will stimulate new theoretical activities for the Southern Ocean. Such activities will be crucial for full understanding the data obtained from the ISOS moored arrays and for deciding what direction new research in the Southern Ocean should go.

3.b. Project Summaries

Dr. Tony Maxworthy of the University of Southern California carried out a number of laboratory experiments on topographic effects in homogeneous and stratified rotating flows over various types of obstacles. In the homogeneous experiments, Maxworthy (1977) compared the effects of various topographic arrangements and how each is affected by changes in the basic parameters. Southern Ocean-type flows were observed in several cases. In particular, the experiments show that the appearance of gyre flows around the coastline of the Antarctic Continent, the shape of streamlines over transverse ridges and the splitting of the main circumpolar flow into at least two filaments south of Australia could be due to the influence of bottom topography. A series of experiments designed to examine in detail some properties of rotating, stratified flows were also carried out (Linden, 1977). The stress-driven flows were strongly stratified and in basic agreement with calculations of Allen (1972) for a stratified annulus. Non-symmetric wave-like motions were observed at high values of the Rossby number.

Dr. Tom Spence of Texas A&M University carried out a series of laboratory experiments in early 1977 under a subcontract from Dr. Maxworthy. Dr. Spence used a rectangular tank with a false bottom for β-plane simulation, and measured drag on a pendulum to look for east-west asymmetry effects related to Southern Ocean Processes. The experiments were carried out over a range of parameters in a homogeneous fluid.

Dr. Michael S. McCartney of the Woods Hole Oceanographic Institute is investigating aspects of current-bottom topography interactions. McCartney (1976) discussed an analytical model of the interaction of a broad eastward baroclinic current with various topographic features of relevance to the Southern Ocean. Zonally elongated ridges intensify the velocity field equatorward of the ridge crest and retard it poleward. This is an explanation for the correlation between the Subantarctic Front and the zonal ridge south of Australia. The interaction can also involve the formation of anticyclonic eddies (warm core) on the poleward side of the ridge. Downstream of the ridge, alternate cyclonic (cold core) and anticyclonic (warm core) eddies may occur.

Allen *et al.* (1975) extended this work to include steady, eastward flow of a stratified fluid in a β-plane channel, with bottom and side-wall topographic disturbances representing features of the Drake Passage. The results show that the combined effects of variable topography, north-south confinement and of β may result in multiple current cores downstream of the topographic disturbance. The spatial scales of these current cores are in reasonable agreement with those found in the Drake Passage.

In addition, McCartney has made some analytical progress in the area of finite amplitude limits to topographic forcing effects on currents. Existing studies generally are restricted to topographic heights h_0 on the order of $HU/(fL) \ll H$. The resultant disturbance is proportional to h_0, while the topographic drag force is proportional to $(h_0)^2$. While it is possible for bottom friction to limit the maximum disturbance, McCartney is working on the idea that there is a finite inertia limitation for non-zero Rossby numbers.

Dr. John Allen of Oregon State University has been working on time-dependent flow in the Drake Passage region. The studies were initiated by considering a linear motion of a barotropic fluid in an infinite β-plane channel, aligned in the east-west direction, with deformations in the channel geometry representing the surface land mass and bottom topographic features of the Drake Passage. The motion is driven by an oscillatory zonal wind stress uniform in space. The characteristics of the response, as a function of the particular topographic constraints representing the Drake Passage and of the forcing frequency, are discussed by Yao (1978).

Yao (1978) also investigated an initial-value problem for the perturbation by a bottom feature to a two-layer, stratified flow on a β-plane. The development in space and in time of the linearized baroclinically unstable disturbance was studied.

Dr. M. Spillane of Nova University has undertaken related topographic effect studies. He has focused initially on the effect of non-zonality of the basic flow in both barotropic and equivalent barotropic systems (McCartney, 1976) on the topography-current interaction. The interaction induces yet another scale of motion into the flow. For a zonally-oriented ridge and eastward zonal current, McCartney (1976) found current intensification on the equatorward side of the ridge, reduction on the poleward side and stationary Rossby waves east of the ridge. Spillane (1978) finds that a meridional component in the basic current causes additional wavy solutions (comparatively long waves) to the west of the topography. These decay rather slowly upstream of the topography. Over the topography these waves give regions of flow intensification and reduction of rather different spatial distribution than for the simple zonal current. The total solutions (long and short waves) seem to give the same result as McCartney's (1976) equatorward intensification, and poleward reduction or reversal.

Spillane (1978) has also shown that when a broad ocean current encounters a large-scale topographic feature, standing Rossby wave patterns can be generated. Short Rossby waves with a scale $L_1 = \sqrt{Q/\beta}$ (Q is the speed of the approaching flow; β is the meridional gradient of f) are generated *east* of the topography. If the zonal scale of the topography, L, is planetary, long standing Rossby waves can be generated *west* of the topography, when the current has a meridional component. The long waves focus the disturbance zonally and produce alternating regions of intensified or reduced zonal flow. The meridional scale that characterizes these zonal bands is the intermediate scale, $L = L_1^{2/3} L^{1/3}$. When the meridional topographic scale is comparable to L, the amplitude of the long wave disturbance dominates. Using multiple scale methods to exploit the scale gap between the planetary, intermediate and Rossby wave scales, the topographically induced pressure and velocity fields due to a zonal ridge are obtained. When the planetary scale flow field is directed poleward, a westward counterflow can occur along the poleward flank of the ridge. The meridional scales of these topographically induced flows are comparable to those observed along the Indian-Antarctic Ridge by Callahan (1971).

Dr. Roland deSzoeke of Oregon State University is studying baroclinic eddy dynamics in the Southern Ocean. This effort derives directly from the current meter data base accumulating at Oregon State and is the first ISOS theoretical project designed to understand processes revealed by empirical analysis of the data. deSzoeke plans to develop models of eddy trans port processes (especially of heat) that can be tested directly with data from the current meter cluster experiments and also to model topographic effects on baroclinic dynamics in the Circumpolar Current.

deSzoeke has also devised an independent method to estimate eddy heat flux from horizontal and vertical arrays of velocity time series only, by assuming geostrophy and hydrostasy. In contrast to eddy heat flux $\overline{v'T'}$, he is attempting to estimate zonally-averaged mean-advected heat flux $\bar{v}\,\bar{\bar{T}}$ from historical hydrographic data. This method was used to help design the 1979 Drake Passage array. Comparison of this method with the direct method of correlation of velocity and temperature fluctuations should illuminate the dynamics of heat-transporting fluctuations.

Work on deSzoeke's baroclinic instability models is also proceeding. He is studying a two-layer model of a front which intersects the ocean surface. The focus is on the time and space scales which are associated with deformations of the front.

Dr. Daniel G. Wright of Woods Hole Oceanographic Institution has also been working on the modeling of baroclinic instability in Drake Passage. Preliminary results from his work suggest that the dominant instability in Drake Passage is due to the bottom shear. That is, it relies on the horizontal temperature gradients due to the bottom shear to maintain the balance in north-south eddy flux of potential vorticity.

Dr. Maurice Rattray and George Dworsky of the University of Washington have begun a theoretical study of the velocity field in the Southern Ocean. This should be a forerunner to modeling the entire (circumpolar) ocean with the objective of calculating variations in the Antarctic Circumpolar Current.

Dr. Yves Desaubies of the Woods Hole Oceanographic Institution has begun analysis and interpretation of meteorological data pertinent to the Southern Ocean and will relate it to the observed fluctuations of the Antarctic Circumpolar Current as being defined by the on-going FDRAKE and DRAKE projects. He intends to develop an analytical stochastic model of the variability induced by atmospheric forcing. This will include the addressing of questions such as: what are the dynamics of the interaction, what are the respective parts played by thermohaline and wind-driven processes and is the forcing local or operating on a large scale?

4. Analysis of Southern Ocean Historical Data

In addition to the field and laboratory experiments being carried out as part of ISOS, considerable effort has gone into the study of the historical physical oceanographic data set of the Southern Ocean. This data set consists of: (1) approximately 34,000 hydrographic stations south of 30°S, a significant fraction being derived from the *Discovery* expeditions of the 1930's, the IGY work in 1957–58 and the *Eltanin* cruises of the 1960's and 1970's; and (2) many tens of thousands of bathythermograph and expendable bathythermograph observations, primarily obtained since 1955.

The data set is not uniform in quality, space or time. The quantity attenuates in winter and towards the south due to presence of extensive sea ice. Even north of the ice fields the winter data set is small. Within the ice, data are from unfortunate ice-bound ships or near antarctic bases where winter activity is carried out. Therefore, the historical data are not useful for the study of winter processes within the sea ice fields and have only limited usefulness for studying winter conditions even in open waters of the Southern Ocean. During summer there are still areas not covered by summer data of reasonable quality, notably in the southwest Pacific Ocean. The summer data base is also small over most of the continental margins of Antarctica.

A great deal of the published work regarding antarctic physical oceanography has been based on historical data. There are a number of scientists using historical data as part of their field or theoretical studies. These include investigation of formation and spreading of Antarctic Intermediate Water and of the paths followed by Antarctic Bottom Water in its course below and circumpolar current from the source region to the northern oceans.

4.a. Southern Ocean Atlas

The objective of the Southern Ocean Atlas project being carried out at the Lamont-Doherty Geological Observatory (LDGO) of Columbia University is to scan all of the available historical data set for the Southern Ocean and the separate out the high-quality data. This high-quality data will then be presented in an atlas of the average oceanographic conditions south of 30°S. In addition, the final edited data set will be available on computer tape for use by interested investigators.

The Atlas Project benefits ISOS directly by providing the background against which the results of the ISOS field experiments, model experiments and theoretical studies may be viewed. In addition, the atlas which will contain the majority of the ISOS data will provide the basis for planning future field or laboratory studies and will offer a means for efficient appraisal of any additional Antarctic data.

Stage I of the Atlas Project was completed in 1975 with the publication of the *USNS Eltanin* Southern Ocean Oceanographic Atlas by A. L. Gordon and E. Molinelli. This atlas is an inexpensive Xerox reproduction of hand-plotted data. Approximately 200 copies were made and have now been distributed. In addition to the atlas, the set of *Eltanin* data were put on magnetic tape, available for loan from LDGO.

Stage II is a compilation of a non-*Eltanin* set of data, which in combination with the *Eltanin* data set would provide a more-or-less uniform circumpolar network of high (although not uniform) quality, deep-reaching hydrographic stations. This stage is presently being completed, concurrent with the beginning of Stage III (the preparation of a full Antarctic Oceanographic Atlas).

Summary of work completed

a. *Eltanin* data—1420 stations. These data were quality controlled during preparation of the *Eltanin* Reports.

b. Recent data, which have been subjected to significant quality control by the originators. This set includes: GEOSECS, HUDSON-70, NEMO, ARIES, GLACIER-73, CONRAD-17 and -18, and PIQUERO, as well as the ISOS data collected in Drake Passage/Scotia Sea and in the New Zealand sector.

c. Stations from the NODC files which have 15 or more observations with the deepest observation at a depth greater than 70% of sonic depth. There are 2929 stations in this category south of 30°S.

d. Stations from the NODC files with 5 or more observations, with the deepest observation between 40% and 70% of sonic depth, and those with less than 15 observations but extending to greater than 70% of sonic depth. The purpose of this tape is to provide additional stations which can be used to increase station density where the *Eltanin*, the 70% tape and the tape of recent stations give only sparse coverage. There are 12,599 stations in this category, but the majority are on the continental shelf of Australia, Argentina and South Africa.

e. A grid point data set is also available. The data set is composed of standard level values at 10° latitude by 20° longitude grid point south of 30°S.

The NODC tapes (items b and c above) have been subjected to a number of quality control procedures to reduce the number of stations to the highest possible quality and provide a nearly uniform circumpolar station network. Our aim is to have a final listing of data for approximately 7000 stations south of 30°S. For sea surface maps for the Atlas the entire NODC file will be used.

The contents of the Southern Ocean Atlas

The Atlas will include the following plates:

1. Station map by symbol, tone and color will identify ship and season, and will indicate when the data used in the Atlas plates are of marginal quality or do not extend to greater than a few hundred meters.
2. Horizontal distributions of potential temperature, salinity, density, oxygen, nutrients (silicate, phosphate and nitrate) at the following levels (in meters): sea surface (seasonal), 200, 500, 1000, 1500, 2000, 3000, 3500, 4000, 5000, 6000 and bottom values.
3. Vertical sections of the same parameters used in the horizontal plates for the following regions: south of South America (Drake Passage); south of Africa; south of New Zealand; south of Australia; southeastern Pacific, Atlantic, Indian; southwestern Pacific, Atlantic, Indian.
4. Scatter diagrams for the stations comprising each of the above mentioned vertical sections, showing: the curves for temperature versus salinity, oxygen and the nutrients.
5. Various core and density surface distributions including the oxygen minimum, salinity maximum and three different potential density surfaces representing sections of the water column.
6. Dynamic height anomalies for the pressure intervals: 0/1000-db, 0/2500-db, 1000/2500-db and 2500/4000-db.
7. A microfiche supplement which uses the grid point data set to generate computer plot/contoured images of horizontal and vertical sections and average vertical curves for temperature, salinity, oxygen, nutrients and Brunt-Väisälä frequency for selected regions.

The Bruce Heezen bottom bathymetry map will be used as base map for the Southern Ocean Atlas plates. This map will be squared off by making the edges of the map tangent to the 30°S parallel.

Completion of the Atlas

At this time, it is anticipated that the Atlas will go to press late in 1980 and be available during 1981.

4.b. Subantarctic Mode Water Formation

Dr. Michael McCartney's (Woods Hole Oceanographic Institution) analysis of existing Southern Ocean data has revealed a family of water types within the upper water column of the subantarctic zone, characterized as thermostads—thick layers of vertically quasi-homogeneous temperature, salinity and oxygen. Immediately north of the circumpolar Subantarctic Front, deep (400–600 m) well-mixed layers are found in late winter. Spring and summer heating isolates (but does not completely erase) these layers beneath the seasonal thermocline as thermostads. The zone in which this active renewal is found is several hundred kilometers wide, but the associated thermostad can be traced much further north—on the order of 2000 kilometers. The thermostads and the often associated dissolved-oxygen maxima can be found as far north as the south equatorial current regions of each southern hemisphere subtropical gyre. This water mass formation and spreading process is similar to that occurring east and south of the Gulf Stream and Kuroshio currents, where the thermostads are called Subtropical Mode Water (STMW). In light of the association of these Southern Ocean thermostads with the circumpolar Subantarctic Front, rather than the Subtropical Fronts (western boundary currents such as the Agulhas Current) the name Subantarctic Mode Water (SAMW) is suggested (McCartney, 1977).

In common with STMW, SAMW contributes substantial volumetric modes to the central water masses, indicating SAMW to be the renewal agent of the high oxygen parts of the main thermocline water of the southern hemisphere subtropical gyres.

Figure 21 shows the east-west variation of the SAMW properties at 32°S in the South Atlantic and Indian Oceans, 40°S in the southeastern Indian Ocean, and 43°S in the South Pacific. Shown is the potential temperature, salinity, and a strength indicator as a function of distance along the sections of the pycnostad. The strength indicator is the Brunt-Väisälä period, proportional to the square root of the vertical thickness of a density increment. Part of the Atlantic data is repeated in the right hand panel, to emphasize the large jump in the local SAMW characteristics that occurs across South America, and for use in a discussion of Antarctic Intermediate Water below.

A lesser break in the smooth trend of characteristics occurs across New Zealand. This break, as well as a number of other regional features makes the New Zealand sector an especially good one for studying the SAMW formation process and other Southern Ocean phenomena. McCartney conducted an experiment in this sector in 1978, as was discussed in Section 2.e.

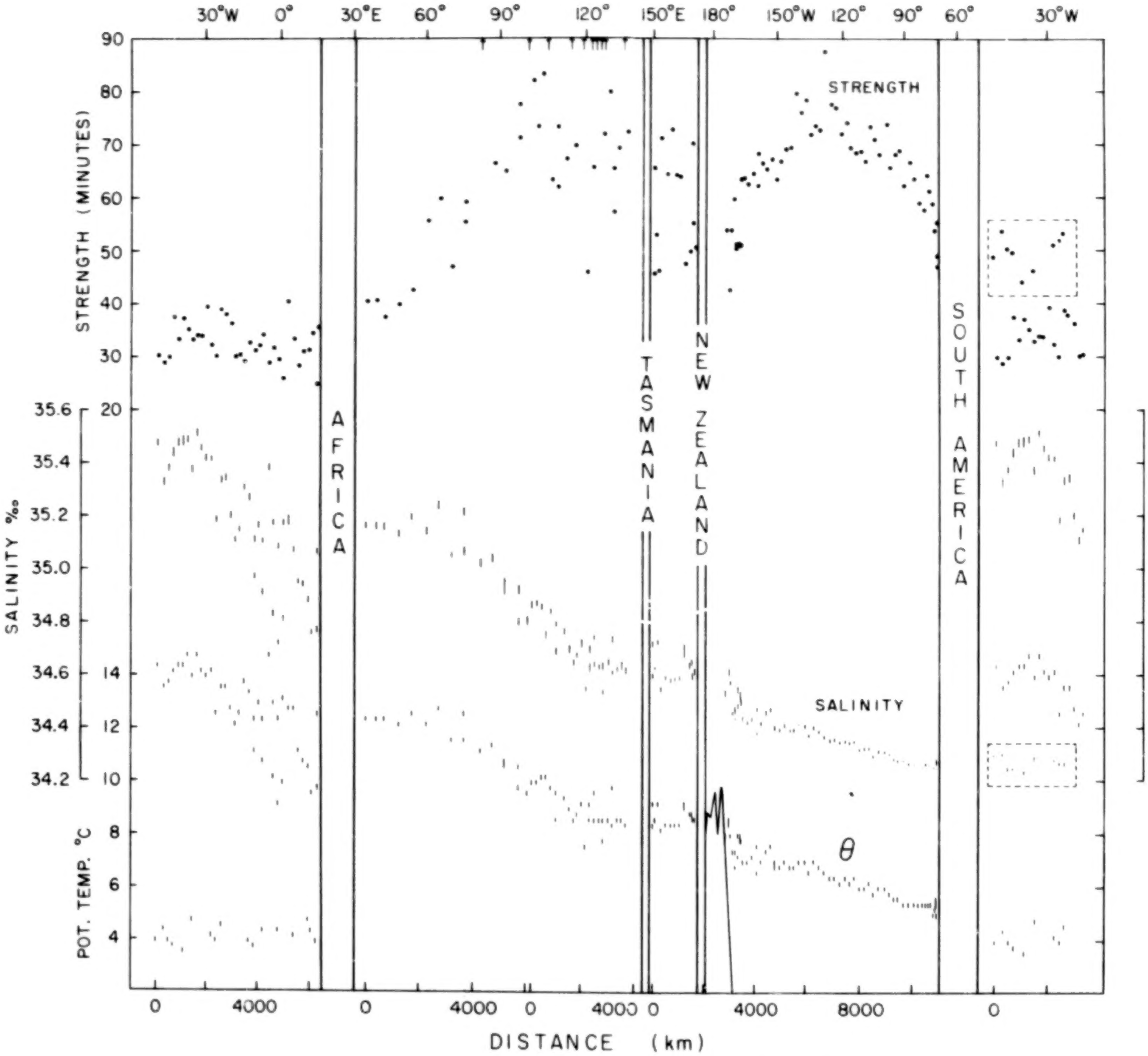


Figure 21. Subantarctic mode water temperature, salinity, and strength (Brunt-Väisälä period) as a function of east-west distance along four zonal sections: 32°S in the South Atlantic Ocean (*R/V Atlantis* cruise 247), 32°S in the southern Indian Ocean (*R/V Atlantis II* cruise 15), 40°S in the southeastern Indian Ocean (*HMAS Diamantina* cruise 1/60) and 43°S in the South Pacific (*USNS Eltanin* cruise 28). The South Atlantic data in the left panel shows two sets of modes, with a cold set being found at temperatures near 4°C. The right panel repeats the western South Atlantic data and in the dashed boxes shows the salinities and strengths of these colder modes. The jagged line east of New Zealand represents the near bottom temperature over the shallow Chatham Rise.

The South Pacific SAMW properties combine with earlier Antarctic Intermediate Water (AAIW) circulation studies such as Johnson (1972) to give a fairly simple formation and recirculation scheme for AAIW. Warmer saltier waters enter the subantarctic zone in the west, but from western boundary currents and from the warmer than 8°C SAMW south of Australia. As this water moves eastward along the northern edge of the Subantarctic Front it is progressively modified by winter convective mixing which seasonally homogenizes the water column, giving the sequence of SAMW displayed in Figure 21. The zone apparently suffers both a net heat loss and a net salt loss. McCartney has suggested that this is accomplished mainly through air-sea heat exchange and the excess of precipitation over evaporation. Joyce and Georgi (see Section 2.d.) say the necessary losses are caused by exchange with the antarctic zone via the interleaving and meso-scale eddies of the Polar Frontal Zone. There is little disagreement about the importance of the seasonal cycle of air-sea heat exchange in causing convective homogenization of the water column.

Part of the low salinity, low temperature mode water at the eastern side of the subantarctic zone within the South Pacific turns north, and as can be seen in the Johnson study, travels north to about 25°S and then west across the Pacific at 25°S, gradually gaining in salinity.

The remainder of the lowest temperature and salinity SAMW passes through the Drake Passage into the South Atlantic. A main axis for its flow is the northward flowing Falkland Current, which hugs the Argentine continental margin, and extends northward beyond 40°S inshore of the warm Subtropical waters of the Brazil Current. In this collision process, the lighter Subtropical waters override the low salinity Falkland Current waters, thereby effecting a meridional exchange, and a resultant injection of the low salinity water into the intermediate depths of the Subtropical gyre.

In Figure 21 these Falkland Current modes appear in the 32°S South Atlantic section, although not at every station, as pycnostads beneath the main thermocline, with associated temperatures from 3.5° to 4.7°C. The boxed data in the right hand panel of the figure shows the salinities and pycnostad strengths of these modes, which are similar to the SAMW values above the main thermocline west of South America.

The remaining low salinity SAMW from the Drake Passage, that which does not enter the South Atlantic subtropical gyre, passes into the Indian Ocean. A second collision and overriding event takes place with the Agulhas Return Current, effecting an injection of low salinity water into the Indian Ocean subtropical gyre. The last remaining part of the Drake Passage origin low salinity SAMW passes south of New Zealand into the central South Pacific. It ceases to be a salinity minimum there, because the lighter South Pacific recirculating SAMW has lower salinity.

In summary, the McCartney AAIW hypothesis indicates AAIW as being "formed" by convective homogenization of the water column in the sector of the subantarctic zone southwest of Chile and within the Drake Passage and that this is circumpolarly the only area at which the AAIW—the coldest, least saline SAMW—contacts the atmosphere. This formation zone falls at the southeastern corner of the South Pacific gyre, so part of this low salinity SAMW recirculates directly anticyclonically around the gyre. The rest passes through the Drake Passage, making its initial penetration of the South Atlantic and South Indian gyres into their southwest corners and from there recirculating anticyclonically around the gyres beneath the subtropical waters.

McCartney and Georgi have proposed a survey of the mode waters of the Southeast Pacific, Drake Passage and Southwest Atlantic for September-October 1980. Related data collection is proposed as part of the DRAKE 79 Moored array. These are discussed in Section 2.e.

4.c. Structure and Spreading of Antarctic Bottom Water

During 1978, Frederick C. Schlemmer II of Texas A&M University completed a dissertation describing the characteristic relations, vertical structure and lateral spreading of Antarctic Bottom Water within the four major oceanic basins adjacent to Antarctica.

Three major layers of Antarctic Bottom Water were identified. Boundaries between these layers occur near the surfaces at potential densities referenced to 4000 db (σ_4) of 46.08 mg cm^{-3}, 46.15 mg cm^{-3} (46.12 mg cm^{-3} in the Marquarie Ridge-Balleny Islands complex and western Southeast Pacific Basin) and 46.21 mg cm^{-3}. These isopycnal surfaces are associated with strata of maximum stability and slope changes in the characteristic relations.

The densest layer of Antarctic Bottom Water ($\sigma_4 \geq 46.21$ mg cm^{-3}) occurs in two separate regions. In the central and western Atlantic-Indian Basin, this layer is comprised of Weddell Sea Bottom Water, characterized by low potential temperature (<0.8°C), salinity (34.63 to 34.67‰) and dissolved silicate concentration (<100μM) and by high dissolved oxygen concentration (>5.7 ml/l). Over the southern Macquarie Ridge, this layer contains Ross Sea Bottom Water, marked by low potential temperature (−0.6 to −0.3°C) and dissolved silicate (102 to 111μM) and by high salinity (34.70 to 34.74‰) and dissolved oxygen (5.5 to 5.7 ml/l).

The layer of Antarctic Bottom Water of intermediate densities extends into all four of the major oceanic basins around Antarctica, but does not reach completely across the Southeast Pacific Basin. This layer is characterized by low silicate values near source regions and, in some regions, by a change in slope of the oxygen-density relations.

The most prominent characteristics of the upper layer of Antarctic Bottom Water (below $\sigma_4 = 46.08$ mg cm^{-3}) are its maximum in dissolved silicate, an increased slope in the dissolved oxygen versus potential stability near its upper boundary and an ubiquitous stratum of maximum stability near its upper layer. Only this uppermost layer extends appreciably northward out of the basins adjacent to Antarctica. Its primary spreading paths are: (1) east of the eastern flank of the Scotia Ridge and through the Argentine Basin; (2) across the Southwest Indian Rise west of Prince Edward Islands; and (3) through the passage between the Crozet Ridge and Kerquelen Plateau. This layer is continuous through all of the basins adjacent to Antarctica, but is interrupted at the Drake Passage. This interruption apparently determines the upper boundary of Antarctic Bottom Water.

5. Availability of ISOS Data

Many types of data have been collected on programs funded by NSF/IDOE as part of the ISOS program. Table 1 contains a listing of the data collected during each field operation, individuals responsible for the data, and where the original data are archived. The major portion of these data have already been submitted to the National Oceanographic Data Center (NODC). The remaining data will be sent to NODC as soon as processing is completed. In addition to the data listed here, considerably more data are being collected during 1979–1980. The DRAKE 79 experiment began during January-February 1979. Also, during September-October 1980, McCartney and Georgi will conduct cruises to study water mass formation in the Argentine Basin, Drake Passage and Southeast Pacific Ocean. The ISOS XBT program will also continue at a reduced level during 1979–1980.

Table 1. Status of ISOS Data

Year	Expedition	Principal Investigator	Data	Location of Data
1974	Ross Sea	V. T. Neal	Under Ice Observations: Temperature, salinity, currents, STD	Oregon State University
1975	FDRAKE 75 *Melville*	Worth D. Nowlin, Jr.	Hydrographic Measurements: Temperature, salinity, oxygen Nutrients: Silicate, phosphate, nitrate, nitrite STD Measurements	Texas A&M University Data Rpt. 77-2-D
1975	FDRAKE 75 *Melville*	R. Dale Pillsbury	Moored Array data: Currents, pressure, temperature, tides	Oregon State University Data Rpt. No. 65, Ref. No. 76–6 Magnetic Tapes Data Rpt. No. 67, Ref. No. 77–8
1975	FDRAKE 75 *Conrad*	Arnold Gordon	Hydrographic Measurements: Temperature, salinity, oxygen Nutrients: Silicate, phosphate	Lamont-Doherty Data Rpt: *Conrad* 18-01
1975	FDRAKE 75 *Islas Orcadas*	Richard Wearn	Hydrographic Measurements: Temperature, salinity, oxygen Nutrients: silicate, phosphate, nitrate, nitrite STD Measurements	University of Washington
1975	FDRAKE 75 All Ships	Worth D. Nowlin, Jr. Arnold Gordon Richard Wearn	XBT Data	Texas A&M University
1976	FDRAKE 76 *Thompson* Legs I & II	Worth D. Nowlin, Jr.	Hydrographic Measurements: Temperature, salinity, oxygen Nutrients: Silicate, phosphate, nitrate, nitrite STD Measurements	Texas A&M University Data Rpt. 78-D-1
1976	FDRAKE 76 *Thompson* Legs I & II	R. Dale Pillsbury	Moored Array data: Currents, pressure, temperature, tides	Oregon State Univer- Data Rpt. No. 68: Ref. 78-2, Mar. 78
1976	FDRAKE 76 *Thompson* Leg III	Terrence Joyce	Hydrographic Measurements: Temperature, salinity, oxygen CTD Measurements	Woods Hole Oceanographic Institution
1976	FDRAKE 76 *Thompson* Leg III	Terrence Joyce/ William Zenk	Vertical Current Meter Profiling Current Meter Temperature means from thermistors	Woods Hole Oceanographic Institution
1976	FDRAKE 76 *Thompson* Leg III	Terrence Joyce/ Louis Gordon	Nutrient Measurements	Woods Hole Oceanographic Institution

Table 1. Status of ISOS Data (Continued)

Year	Expedition	Principal Investigator	Data	Location of Data
1976	FDRAKE 76 *Thompson* Leg III	Gunnar Kullenberg	Optical Measurements	Institute of Physical Oceanography, Univ. of Copenhagen Denmark
1976	FDRAKE 76 *AGS Yelcho*	Steven Patterson	Surface Measurements XBT Data	Texas A&M University
1976	FDRAKE 76 *Thompson* Legs I & II	Worth D. Nowlin, Jr.	XBT Data	Texas A&M University
1976	FDRAKE 76 *Thompson* Leg III	Terrence Joyce	XBT Data	Woods Hole Oceanographic Institution
1977	FDRAKE 77 *Melville*	Worth D. Nowlin, Jr.	Hydrographic Measurements: Temperature, salinity, oxygen	Texas A&M University
1977	FDRAKE 77 *Melville*	Worth D. Nowlin, Jr.	XBT Data	Texas A&M University
1977	FDRAKE 77 *Melville*	R. Dale Pillsbury	Moored Array data: Currents pressure, temperature	Oregon State University
1977	FDRAKE 77 *Melville*	Richard Wearn/ D. James Baker, Jr.	Pressure Recorder Data	University of Washington
1977	FDRAKE 77 *AGS Yelcho*	Worth D. Nowlin, Jr.	XBT Data	Texas A&M University
1977	FDRAKE 77 *AGS Yelcho*	Richard Wearn/ D. James Baker, Jr.	Pressure Recorder Data	University of Washington
1977	FDRAKE 77 *AGS Yelcho*	R. Dale Pillsbury	Moored Array Data: Currents temperature, pressure	Oregon State University
1977	*Zubov*	Louis Gordon	Hydrographic Measurements: Temperature, salinity	Oregon State University
1977	*Zubov*	William J. Emery	XBT Data	University of British Columbia
1977	XBT Program	William J. Emery		University of British Columbia
	Yelcho		XBT Data and Surface Log	
	Burton Isl.		XBT Data and Surface Log	
	Hero		XBT Data	
	Northwind		XBT Data and Surface Log	
	Nella Dan		XBT Data	
	Thalla Dan		XBT Data	
1978	RIDGE *Tangaroa*	Harry Bryden	Moored Array data: Currents, temperature, pressure	Woods Hole Oceanographic Institution
1978	RIDGE *Tangaroa*	Stanley Hayes	CTD Measurements	Pacific Marine Environmental Lab.
1978	Water Mass Renewal & Circulation Studies *Knorr*	Michael McCartney	CTD Measurements	Woods Hole Oceanographic Institution
		William Jenkins	^{3}H/^{3}He Measurements	Woods Hole Oceanographic Institution
1978	RIDGE and Dynamics of Eddies & Interleaving of Water Masses *Knorr*	Harry Bryden	Moored Array data: Currents temperature, pressure Thermistor Chain Data	Woods Hole Oceanographic Institution
		Terrence Joyce	CTD Measurements XBT Data	Woods Hole Oceanographic Institution
1979	DRAKE 79 *Melville*	Worth D. Nowlin, Jr.	Hydrographic Measurements: Temperature, salinity, oxygen STD Measurements	Texas A&M University
1979	DRAKE 79	R. Dale Pillsbury	Moored Array data: Currents pressure, temperature, tides	(Array now in place)
1979	DRAKE 79 *Melville*	Richard Wearn/ D. James Baker, Jr.	Pressure Recorder Data	(Meters now in place)
1979	DRAKE 79 *Melville*	Worth D. Nowlin, Jr.	XBT Data	Texas A&M University
1979	DRAKE 79 *AGS Yelcho*	Worth D. Nowlin, Jr.	Hydrographic Measurements: Temperature and salinity	Texas A&M University
1979	DRAKE 79 *AGS Yelcho*	Worth D. Nowlin, Jr.	XBT Data	Texas A&M University

6. International Cooperation within ISOS

There have been many ISOS activities involving international cooperation. Representatives from Argentina, Australia, Canada, Chile, Denmark, England, France, Japan, Norway, South Africa, USSR and West Germany have attended annual meetings of the ISOS Scientific Council. As a result of these meetings collaboraton and data exchange between scientists from these countries and ISOS principal investigators have been arranged. Foreign participants have been involved in all ISOS cruises on US vessels, and ISOS investigators have cooperated in cruises of vessels operated by Argentina, New Zealand, Chile and the USSR. A brief summary of international cooperation in ISOS field programs follows.

International Cooperation in ISOS Field Programs

1975. The principal area of cooperation between US and foreign scientists during 1975 was the field experiment FDRAKE 75. One of the ships used during FDRAKE 75 was the *ARA Islas Orcadas* of the Argentine Hydrographic Service. Scientists and technicians from the University of Washington, Texas A&M University, Instituto Antartico Argentino, Oregon State University and Universidad Catolcia de Valparaiso (Chile) were at sea from 10 January to 3 March 1975 studying the physical and chemical properties of the Drake Passage and western Scotia Sea.

Observers from the Instituto Hidgrografio de la Armada de Chile and Servicio de Hidrografico Naval de Argentina participated in the cruise of *Melville* in the Drake Passage and western Scotia Sea region from 19 February to 31 March 1975. Observers from the Instituto Antartico Argentino worked on board *R/V Conrad* from 6 February to 13 March 1975.

1976. Two ships operating out of Punta Arenas, Chile were used in FDRAKE 76: *AGS Yelcho* of the Chilean Navy and *R/V Thomas G. Thompson* of the University of Washington. The *AGS Yelcho* had scientists from both Chile and the USA aboard, with Hellmuth Sievers of the Chilean Hydrographic Institute and Steven Patterson of Texas A&M University acting as co-chief scientists. Observers from both Chile and Argentina were also aboard *Thompson*. In addition, W. Zenk of West Germany and Gunnar Kullenberg of Denmark were aboard *Thompson* for the Polar Front work during Leg III. Zenk made measurements of vertical velocities near the frontal zone. Kullenberg performed light scattering and transmission experiments.

Near Livingston Island, *R/V Thompson* rendezvoused with the Soviet research vessel *Professor Viese*, which had been making current measurements and hydrographic/STD observations to the west of *Thompson* activities. At rendezvous salinity, oxygen and nutrient standards were exchanged and simultaneous hydrographic and STD measurements were made for intercalibration.

1977. Both Chilean and Argentine observers participated in the field work in Drake Passage during January and February 1977 (FDRAKE 77). The Chilean naval vessel *AGS Yelcho* was used to recover the 1977 current meter and pressure gauge array during December 1977. The scientific team aboard *Yelcho* included personnel from the Instituto Hidrografico de la Armada de Chile, University of Washington, Texas A&M University and Oregon State University.

The research vessel *Professor Zubov*, of the Arctic and Antarctic Research Institute of the USSR, was used for a 25-day USSR-USA cooperative cruise in the Southern Ocean south of Australia during January-February 1977. William Emery of Texas A&M University and Steve Hagar and Sandy Moore of Oregon State University participated in this cruise. During the cruise another intercomparison of Soviet and USA analytical techniques for determination of salinity and nutrients was carried out.

During the 1976–77 austral summer, the ISOS XBT survey program was initiated by William Emery of Texas A&M University. Mr. Hellmuth Sievers (Instituto Hidrografico de la Armada de Chile) and Mr. Robert Edwards (CSIRO, Australia) have cooperated in this project by supervising and taking of XBT data from the *AGS Yelcho* (Chile), *Thalla Dan* (Australia) and *Nella Dan* (Australia) as they were supplying Antarctic land stations.

1978. During March-April, the *R/V Tangaroa* of New Zealand was used to deploy the RIDGE experiment current meter array south of New Zealand. This work is under the overall direction of Harry Bryden of the Woods Hole Oceanographic Institution.

Scientists from the Arctic and Antarctic Research Institute of the USSR, the Australian National University and the New Zealand Oceanographic Institute participated in the ISOS RIDGE cruises aboard the *R/V Knorr* during November-December 1978.

The Arctic and Antarctic Research Institute of the USSR invited the US (ISOS) scientists to participate in their POLEX-South activities south of Africa during December 1978-March 1979.

Dr. Johann R. Lutjeharms of the National Research Institute for Oceanology, Republic of South Africa, participated in the ISOS XBT program during the austral summer of 1978–1979. He obtained his XBTs through the US FGGE office.

1979. Scientists and technicians from the Argentine Antarctic Institute, Argentine Hydrographic Service and the Chilean Hydrographic Institute participated in DRAKE 79 operations aboard the *R/V Melville*. The Argentines supplied 3 acoustic releases and 10 current meters (as well as technical support) for use in the DRAKE 79 moored array program. The Chileans supplied personnel to aid in the DRAKE 79 hydrographic program. In addition, the Chilean Navy aided in all the logistic arrangements necessary for the success of the first phase of DRAKE 79. Included in these arrangements were the storage of all ISOS equipment in Chilean Naval warehouses and transportation of this equipment to/from the *Melville*.

The *AGS Yelcho* of the Chilean Navy was used for the second operational phase of DRAKE 79 activities. During April-May 1979 a team of technicians from the Chilean Hydrographic Institute, supervised by a team of US ISOS personnel, made a hydrographic survey over the DRAKE 79 moored array (Fig. 9).

The *AGS Yelcho* will also be used to make XBT measurements in the vicinity of the DRAKE 79 moored array during the early austral winter of 1979–1980.

1980–1981. Once again, Argentina and Chile will participate in DRAKE 79 operations.

The Chilean Hydrographic Institute has offered the use of the *AGS Yelcho* for ISOS-related work during 1980.

The Argentine Hydrographic Service and Antarctic Institute plan to begin an investigation of the Scotia Arc area during 1980. They have invited ISOS scientists to participate.

The *R/V Tangaroa* of New Zealand is scheduled to recover the site mooring at 49°23.5′S, 170°30.2′W and make hydrographic measurements in support of this area during the period 2–24 April 1980 as a part of RIDGE.

The Arctic and Antarctic Research Institute of the USSR has plans for a multi-ship experiment south of Australia-New Zealand during 1980. ISOS investigators have been invited to participate in these cruises. The AARI also plans to support Arnold Gordon's Weddell Sea Polyna work during 1981. Tentative plans call for the use of the *Somov*.

ISOS/POLEX-South

During 1976 there was a US/USSR POLEX-ISOS meeting in Leningrad, USSR. Papers were presented which summarized the ongoing work in the ACC of both the POLEX-South and ISOS programs. Plans were made for future cooperative efforts between these groups.

A second ISOS/POLEX-South meeting was held on 13–15 June 1978 in Boston Massachusetts. At this meeting papers were presented by ISOS investigators and scientists from the Arctic and Antarctic Research Institute of the USSR. At this meeting four specific areas of further US-USSR cooperation in the Southern Ocean were identified. These areas are: (1) US participation in the USSR field experiment in the region south of Africa during the austral summer of 1978–1979; (2) Cooperative US-USSR studies during the austral summer of 1979–1980 in the Drake Passage, Scotia Sea and southeastern Pacific Ocean from US vessels and in the areas south of Australia from Soviet vessels; (3) Cooperative studies in the field of theoretical modeling of the Southern Ocean with exchange of scientists to begin no earlier than the second half of 1979; and, (4) Cooperative studies of the Weddell Polyna, a large ice-free region which often develops near 10°W, 65°S in the austral winter. In addition, future plans call for the third ISOS/POLEX-South workshop to be held in Leningrad, USSR, during the spring of 1981.

Other International Cooperation

Scientists and technicians from foreign countries also worked on ISOS related projects for varying periods during 1977. A brief listing follows

Alberto Piola and Raul Guerrero, Naval Hydrographic Service, Buenos Aires, Argentina, visiting Lamont-Doherty Geological Observatory, processing hydrographic data from *Islas Orcadas* Cruise 13/14-77.

Jose Gallo and Mario Marino, Antarctic Institute, Buenos Aires, Argentina, visiting Oregon State University, studying mooring and release technology and the processing of current meter data.

Dr. Chris Fandry, Monash University, Melbourne, Australia, visiting Oregon State University for one year, analyzing current meter records from FDRAKE.

Dr. George Cresswell, CSIRO, Cronulla, Australia, visiting Texas A&M University, studying ocean drifter data.

Mr. Hellmuth Sievers, Naval Hydrographic Institute, Valparaiso, Chile, visiting Texas A&M University, studying XBT and hydrographic data from Drake Passage and near the Chilean coast.

Jose Gallo and Claudio Bertollo visited Texas A&M University to reduce data from *Islas Orcadas* cruise 09-76 during the 1976 austral winter.

More detailed information concerning foreign cooperation with the ISOS program may be found in the ISOS International Newsletters. These newsletters are prepared by the ISOS International Coordinator, Dr. Victor T. Neal of Oregon State University, with assistance from W. D. Nowlin, Jr. and the staff of the

ISOS project office at Texas A&M University. They summarize ISOS activities and related work in the Southern Ocean.

Dr. Neal and other members of the ISOS Scientific Council have made a number of visits to foreign institutions and participated in many international meetings for the purpose of expanding international cooperation with the program.

As of the spring of 1979, Dr. Neal has stopped serving as the ISOS International Coordinator. His duties are now being handled by the ISOS Administrative Office at Texas A&M University.

References

Allen, J. S. 1972. Upwelling of a stratified fluid in a rotating annulus: steady state. Part 1. Linear theory. *Journal of Fluid Mechanics, 56:* 429–445.

——, M. S. McCartney and T. Yao. 1975. Topographically-induced jets in a zonal channel with application to the Drake Passage. Program, 1975 Annual Fall Meeting, American Geophysical Union.

Baker, D. J., Jr., W. D. Nowlin, Jr., R. D. Pillsbury, and H.L. Bryden. 1977. Antarctic Circumpolar Current: Space and Time Fluctuations in the Drake Passage. *Nature, 268* (5622): 696–699.

Bryden, H. L. 1979. Poleward heat flux and conversion of available potential energy in Drake Passage. *Journal of Marine Research, 34* (1): 1–22.

Callahan, J. E. 1971. Velocity structure and flux of the Antarctic Circumpolar Current south of Australia. *Journal of Geophysical Research, 76* (24): 5859–5864.

Deacon, G. E. R. 1937. The hydrology of the Southern Ocean. *Discovery Reports, 15:* 1–124.

Emery, W. J., and V. G. Savchenko. 1977. Cyclonic rings south of Australia. *Polymode News,* No. 24, April 8. (unpublished manuscript)

Fandry, C., and R. D. Pillsbury. 1979. On the estimation of absolute geostrophic volume transport applied to the Antarctic Circumpolar Current. *Journal of Physical Oceanography, 9* (3): 440–455.

Gordon, A. L. 1975. Contributions of *R/V Conrad* to FDRAKE, 1975. *Antarctic Journal of the United States, X:* 142–143.

——, and E. Molinelli, 1975. *USNS Eltanin* Southern Ocean Oceanographic Atlas, Cruises 4–55, June 1962–November 1972. Lamont-Doherty Geological Observatory Contribution No. 2256.

——, D. T. Georgi and H. W. Taylor. 1977. Antarctic Polar Front Zone in the Western Scotia Sea - Summer 1975. *Journal of Physical Oceanography,* 7 (3): 309–328.

——, and W. D. Nowlin, Jr. 1978. Basin waters of the Bransfield Strait. *Journal of Physical Oceanography, 8* (2): 258–264.

——, E. Molinelli and T. Baker. 1978. Large-scale relative dynamic topography of the Southern Ocean. *Journal of Geophysical Research, 83* (C6): 3023–3032.

Gordon, L. I., G. C. Anderson and W. D. Nowlin, Jr. 1977. Results of an intercalibration at sea of hydrographic and chemical observations and standards aboard the USSR ship *Professor Viese* and the US Research Vessel *T. G. Thompson* during FDRAKE 76. ISOS Tech. Rept. Oregon State University Reference 77-7, 23 pp.

Hayes, S. P., and W. Zenk. 1977. Moored temperature time series in the Polar Front Zone during FDRAKE 1976. *Antarctic Journal of the United States. XII* (4): 50–51.

Heath, R. A. 1976. Models of the diffusive-advective balance at the Subtropical Convergence. *Deep-Sea Research, 23:* 1153–1164.

——, H. L. Bryden, S. P. Hayes. 1978. Interaction of the Antarctic Circumpolar Current with topography south of New Zealand. Cruise report of the *R/V Tangaroa*, New Zealand Oceanographic Institute, 5 pp.

Ingersoll, A. P. 1969. Inertial Taylor columns and Jupiter's Great Red Spot. *Journal of Atmospheric Sciences, 26:* 744–752.

Johnson, R. E. 1972. Antarctic Intermediate Water in the South Pacific. In: *Oceanography of the South Pacific, 1972,* comp. R. Fraser. UNESCO, Wellington, 1973.

Joyce, T. M., C. Dahm, J. Dean, D. Georgi, G. Kullenberg, M. McCartney, R. Millard, D. Moller, J. Toole, A. Voorhis and W. Zenk. 1976. Observations of the Antarctic Polar Front during FDRAKE 76: A cruise report. Woods Hole Oceanographic Reference No. 76-74. (unpublished manuscript)

——. 1976. Observations of the Polar Front Zone during FDRAKE 1976: *R/V Thompson* Leg 3. *Antarctic Journal of the United States. XI* (3): 157–158.

——. 1977. A note on lateral mixing of water masses. *Journal of Physical Oceanography,* 7 (4): 626–629.

——, and S. L. Patterson. 1977a. Stirring processes within the Antarctic Polar Front Zone. *Antarctic Journal of the United States, XII* (4): 51–52.

——, and ——. 1977b. Cyclonic ring formation at the Polar Front Zone in the Drake Passage. *Nature, 265* (5590): 131–133.

——, W. Zenk and J. Toole. 1978. The anatomy of the Antarctic Polar Front in the Drake Passage. *Journal of Geophysical Research, 83* (C12): 6093–6114.

Linden, P. F. 1977. The flow of a stratified fluid in a rotating annulus. *Journal of Fluid Mechanics, 79:* 435–477.

Maxworthy, T. 1977. Topographic effects in rapidly rotating fluids: Flow over a transverse ridge. *Journal of Applied Mathematics and Physics (ZAMP), 28:* 853–864.

Masuzawa, J. 1969. Subtropical mode water. *Deep-Sea Research, 16:* 463–472.

McCartney, M. S. 1976. The interaction of zonal currents with topography with applications to the Southern Ocean. *Deep-Sea Research, 23:* 413–427.

——. 1977. Subantarctic mode water. In: *A Voyage of Discovery.* M. Angel, Ed., Pergamon Press, 103–119.

Neal, V. T. 1974. International Southern Ocean Studies, 1975–1976. *Antarctic Journal of the United States, IX* (6): 289–290.

Nowlin, W. D., Jr., S. L. Patterson, R. D. Pillsbury and G. C. Anderson. 1975. Contributions of *R/V Melville* to FDRAKE 1975. *Antarctic Journal of the United States, X*: 144–146.

——, R. D. Pillsbury, L. I. Gordon, G. C. Anderson and D. J. Baker, Jr. 1976. Contributions of the *R/V Thompson* legs 1 and 2 to FDRAKE, 1976. *Antarctic Journal of the United States. XI* (3): 154–156.

——, T. Whitworth, III and R. D. Pillsbury. 1977. Structure and transport of the Antarctic Circumpolar Current at Drake Passage from short-term measurements. *Journal of Physical Oceanography, 7:* 788–802.

——, and R. D. Pillsbury. 1979. DRAKE 79 operations aboard *R/V Melville*. (Submitted to *Antarctic Journal of the United States,* May).

Patterson, S. L. 1977. A cyclonic ring north of the Polar Front in the Drake Passage. *Polymode News,* No. *21*, January. (unpublished manuscript)

——, and H. A. Sievers. 1976. Contributions of *AGS Yelcho* to FDRAKE 1976. *Antarctic Journal of the United States, XI* (3): 158–159.

Pillsbury, R. D., J. S. Bottero and R. E. Still. 1976. Currents, temperature and pressure in the Drake Passage during FDRAKE 75, January-March 1975. School of Oceanography, Oregon State University, A compilation of observations from moored current meters, Vol. *IX*, Data Report 65, Ref. 76–6, June 1976.

——, ——, and ——. 1977. Currents, temperature and pressure in the Drake Passage during FDRAKE 75, February 1975–February 1976. School of Oceanography, Oregon State University, A compilation of observations from moored current meters, Vol. *X*, Data Report 67, Ref. 77–8, August 1977, 117 pp.

Ridgway, H. M. 1975. Hydrology of the Bounty Island region. Memoir 75. New Zealand Oceanographic Institute.

Schlemmer, F. S., II. 1978. Structure and spreading of Antarctic Bottom Waters in oceanic basins adjacent to Antarctica. Ph.D. dissertation, Texas A&M University, College Station, TX, 127 pp.

Spillane, M. 1978. Topographic generation of intermediate-scale motions by wind-driven currents—a model for the circulation in the vicinity of the Indian-Antarctic Ridge. *Dynamics of Atmospheres and Oceans, 2,* 427–453.

Wearn, R. B., Jr., and P. K. Park. 1975. Contributions of *ARA Islas Orcadas* to FDRAKE 1975. *Antarctic Journal of the United States, X*: 141–142.

Wearn, R. B., Jr, and D. J. Baker, Jr. 1980a. Bottom pressure measurements across the Antarctic Circumpolar Current and their relation to the wind. Submitted to *Deep Sea Research*.

Wearn, R. B., Jr. and D. J. Baker, Jr. 1980b. Wind stress variability over the Southern Ocean, 1976–1978. Submitted to *Monthly Weather Review*.

Whitworth, T., III. 1977. FDRAKE 77. *Antarctic Journal of the United States, XII* (4): 48–49.

Worthington, L. V. 1959. The 18° water in the Sargasso Sea. *Deep-Sea Research, 5:* 297–305.

Yao, T. 1978. Some effects of topography and mean flow on low frequency fluctuations. Ph.D. thesis, Oregon State University, Corvallis.

Appendix I

Publications

Baker, D. J., Jr. 1975. Currents, fronts, and botton water. *Oceanus, 18* (4): 8–15.

Baker, D. J., Jr. 1975. U.S. contribution to Southern Ocean Dynamics. *Reviews in Geophysics and Space Physics, 13* (3): 615–617.

Baker, D. J., Jr. 1979. Polar Oceanography II: Southern Ocean. *Reviews of Geophysics and Space Physics, 17* (7): 1578–1585.

——, W. D. Nowlin, Jr., R. D. Pillsbury and H. L. Bryden. 1977. Antarctic circumpolar current: Space and time fluctuations in the Drake Passage. *Nature, 268* (5622): 696–699.

Baker, D. J., Jr. 1979. Ocean-atmosphere interaction in high southern latitudes. *Dynamics of Atmospheres and Oceans, 3:* 213–229.

——, and W. D. Nowlin, Jr. 1978: Antarctic Ocean. *In:* McGraw Hill Yearbook of Science and Technology 1978, pp. 89–91.

Bryden, H. L. 1979. Poleward heat flux and conversion of available potential energy in Drake Passage. *Journal of Marine Research, 37* (1): 1–22.

——, and R. D. Pillsbury. 1977. Variability of deep flow in the Drake Passage. *Journal of Physical Oceanography, 7:* 803–810.

Emery, W. J. 1977: The errors in inferring salinity from sound velocity. *Journal of Physical Oceanography, 7* (2): 293–297.

——. 1977. Antarctic Polar Frontal Zone from Australia to the Drake Passage. *Journal of Physical Oceanography, 7* (6): 811–822.

Fandry, C., and R. D. Pillsbury. 1979. On the estimation of absolute geostrophic volume transport applied to the Antarctic Circumpolar Current. *Journal of Physical Oceanography, 9* (3): 449–455.

Georgi, D. T. 1978. Fine structure in the Antarctic polar frontal zone: its characteristics and possible relationship to internal waves. *J. Geophys. Res., 83:* 4579–4588.

Georgi, D. 1979. Modal properties of AAIW in the southeast Pacific and the South Atlantic. *Journal of Physical Oceanography, 9* (3): 456–468.

Gordon, A. L., and H. W. Taylor. 1975. Seasonal change of Antarctic Sea ice cover. *Science, 187:* 346–347.

——, D. T. Georgi and H. W. Taylor. 1977. Antarctic Polar Front Zone in the Western Scotia Sea—Summer 1975. *Journal of Physical Oceanography, 7* (3): 309–328.

——, and W. D. Nowlin, Jr. 1978. The basin waters of the Bransfield Strait. *Journal of Physical Oceanography, 8* (2): 258–264.

——, and M. R. Rodman. 1978. Southern Ocean temperature gradient near 2°C. *In: A Voyage of Discovery.* M. Angel, Ed., Pergamon Press, pp. 85–102.

——, E. Molinelli and T. Baker. 1978. Large-scale relative dynamic topography of the Southern Ocean. *Journal of Geophysical Research,* 83(C6): 3023–3032.

Joyce, T. M. 1977. A note on lateral mixing of water masses. *Journal of Physical Oceanography, 7* (4): 626–629.

——, and S. L. Patterson. 1977. Cyclonic ring formation of the Polar Front Zone in the Drake Passage. *Nature, 265* (5590): 131–133.

——, W. Zenk and J. M. Toole. 1978. The anatomy of the Antarctic Polar Front in the Drake Passage. *Journal of Geophysical Research, 83* (C12): 6093–6114.

Kirwan, A. D., Jr. 1975. Oceanic velocity gradients. *Journal of Physical Oceanography, 5* (4): 729–735.

——, ——, M. S. Chang and R. Molinari. 1975. The effect of wind and surface currents on drifters. *Journal of Physical Oceanography, 5* (2): 361–368.

——. 1977. Specifications for some satellite applications for data telemetry and platform location. Part III, Chapter 14 of *Earth Observation Systems for Resource Management and Environmental Control.* D. J. Clough and L. W. Morley, Eds., Plenum Press.

Legeckis, R. 1977. Oceanic Polar Front in the Drake Passage—satellite observations during 1976. *Deep-Sea Research, 24:* 701–704.

Linden, P. F. 1977. The flow of a stratified fluid in a rotating annulus. *Journal of Fluid Mechanics, 79:* 435–477.

Lutjeharms, J. R. E. 1976. The Agulhas current system during the north-east monsoon season. *Journal of Physical Oceanography, 6:* 665–670.

——. 1977. The need for oceanologic research in certain areas of the southwest Indian Ocean. *South African Journal of Science, 73* (2): 40–43.

——. 1977. Time variations in the spatial scales and intensities of ocean circulation near the Cape of Good Hope. *Tellus, 29* (4): 375–381.

——, and D. J. Baker, Jr. 1979. Intensity and scales of motion in the Southern Ocean. *South African Journal of Science, 75:* 179–182.

Maxworthy, T. 1977. Topographic effects in rapidly rotating fluids: Flow over a transverse ridge. *Journal of Applied Mathematics and Physics (ZAMP), 28:* 853–864.

McCartney, M. S. 1976. The interaction of zonal currents with topography with applications to the Southern Ocean. *Deep-Sea Research, 23:* 413–427.

——. 1977. Subantarctic mode water. *In: A Voyage of Discovery.* M. Angel, Ed., Pergamon Press, pp. 103–119.

Neal, V. T. 1977. International Southern Ocean Studies. In: *Desarrolle la Antarctica.* F. O. Vicuna and A. S. Aroya, Eds., Instituto de Estaudios Internacionales de la Universidad de Chile, pp. 307–318.

Nowlin, W. D., Jr., T. Whitworth, III, and R. D. Pillsbury. 1977. Structure and transport of the Antarctic Circumpolar Current at Drake Passage from short-term measurements. *Journal of Physical Oceanography, 7:* 788–802.

Pillsbury, R. D., T. Whitworth, III, W. D. Nowlin, Jr. and F. Sciremammano. 1979. Currents and temperatures as observed in Drake Passage during 1975. *Journal of Physical Oceanography,* 9(3).

Savchenko, V. R., W. J. Emery and O. A. Vladimirov. 1978. A cyclonic eddy in the Antarctic Circumpolar Current south of Australia: Results of Soviet-American observations aboard the *R/V Professor Zubov. Journal of Physical Oceanography, 8* (5): 825–837.

Sciremammano, F. 1979. Observations of Antarctic Polar Front motions in a deep water expression. *Journal of Physical Oceanography, 9* (1): 221–226.

Sievers, H. A., and W. J. Emery. 1978: Variability of the Antarctic Polar Frontal Zone in the Drake Passage—Summer 1976–77. *Journal of Geophysical Research, 83* (C6): 3010–3022.

Spillane, M. 1978. Topographic generation of intermediate-scale motions by wind-driven currents—a model for the circulation in the vicinity of the Indian—Antarctic Ridge. *Dynamics of Atmospheres and Oceans, 2,* 427–453.

Taylor, H. W., A. L. Gordon and E. Molinelli. 1978. Climate characteristics of the Antarctic Polar Front Zone. *Journal of Geophysical Research, 83* (C9): 4572–4578.

Treshnikov, A. F., R. D. Pillsbury, W. D. Nowlin, Jr., E. I. Sarukhanyan and N. P. Smirnov. 1977. A comparison of summer current measurements in the Drake Passage. *Journal of Physical Oceanography, 7:* 610–614.

Wust, G. 1975. *The Stratosphere of the Atlantic Ocean.* Translation by W. J. Emery. Amerind Pub. Co., New Delhi, India.

Data Reports

Gordon, A. L. and E. Molinelli. 1975. *USNS Eltanin* Southern Ocean Oceanographic Atlas, Cruises 4–55, June 1962–November 1972. Lamont-Doherty Geological Observatory Contribution No. 2256.

Gordon, L. I., G. C. Anderson and W. D. Nowlin, Jr. 1977. Results of an intercalibration at sea of hydrographic and chemical observations and standards aboard the USSR ship *Professor Viese* and the US research vessel *T. G. Thompson* during FDRAKE 76. ISOS Tech. Rept. OSU Ref. 77–7, 23 pp.

Joyce, T. M., J. Dean, M. McCartney, R. Millard, D. Moller, A. Voorhis, C. Dahm, D. Georgi, G. Kullenberg, J. Toole and W. Zenk. 1976. Observations of the Antarctic Polar Front during FDRAKE 76: A cruise report. Woods Hole Oceanographic Institution 76–74, Unpublished manuscript.

Lutjeharms, J. R. E. 1976. A catalogue of sea level measurements in the Southern Ocean. Department of Oceanography, University of Washington Spec. Rpt. No. 63, Ref. M76–28, May 1976.

Nowlin, W. D., Jr., T. Whitworth, III, L. I. Gordon and G. C. Anderson. 1977. Oceanographic station data collected aboard *R/V Melville* during FDRAKE 75. Ref. 77–2d, May 1977. Texas A&M Research Foundation.

Pillsbury, R. D., J. S. Bottero and R. E. Still. 1976. Currents, temperature and pressure in the Drake Passage during FDRAKE 75, January–March 1975. School of Oceanography, Oregon State University, A compilation of observations from moored current meters, Vol. IX, Data Rept. 65, Ref. 76–6, June 1976.

——, —— and ——. 1977. Currents, temperature and pressure in the Drake Passage during FDRAKE 75, February 1975–February 1976. School of Oceanography, Oregon State University. A compilation of observations from moored current meters, Vol. X, Data Rpt. 67, Ref. 77–8, August 1977, 117 pp.

Sciremannano, F., R. D. Pillsbury, J. S. Bottero and R. E. Still. 1978. A compilation of observations from moored current meters, Vol. XI. Currents, temperature and pressure in the Drake Passage during FDRAKE 76, February 1976–January 1977. School of Oceanography, Oregon State University, Data Rept. 68, Ref. 78–2, 77 pp.

Wearn, R. B., Jr., S. W. Hager, and L. S. Green. 1979. Hydrographic and STD data collected aboard *ARA Islas Orcadas* during FDRAKE 75. Applied Physics Laboratory, University of Washington, Data Report No. APL-UW 7913, 257 pp.

Whitworth, T., III, W. D. Nowlin, Jr., L. I. Gordon and G. C. Anderson. 1978. Oceanographic data collected aboard *R/V T. G. Thompson* during FDRAKE 76, Legs I and II. Department of Oceanography, Texas A&M University, Data Rept., Ref. 78-1-D, 245 pp.

Worley, S. J. and W. D. Nowlin, Jr. 1978. Oceanographic Data Collected Aboard *R/V Melville* during January–February 1977 as a part of FDRAKE 77. Department of Oceanography, Texas A&M University, Data Report, Ref. 78-12-T, 137 pp.

Worley, S. J. 1979. Data compilation from Southern Ocean lagrangian drifter observation (SOLO) during December 1977–May 1978 beginning along 170°E longitude. Department of Oceanography, Texas A&M University, Data Report, Ref. 79-6-T, 11 pp.